INTERDISCIPLINARY ASSESSMENT OF THE SKATE FISHERY IN THE GULF OF ALASKA

By

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A Dissertation Submitted in Partial Fulfillment of the Requirements

for the Degree of

Doctor of Philosophy

in

Fisheries

University of Alaska Fairbanks

December 2017

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Abstract

Skates are common bottom-dwelling fishes and valuable non-target species in Gulf of Alaska fisheries. Although there is little demand for skates in the United States, markets in Europe and Asia are fueling desires for additional fishing opportunities on skates in Alaska. Management agencies, however, have been hesitant to allow increased harvests due to the lack of information on the ecology and population dynamics of skates, and the bioeconomics of skate fisheries. Specifically focusing on the two most commonly landed skate species in the Gulf of Alaska (GOA), the big skate (*Beringraja binoculata*) and the longnose skate (*Raja rhina*), I conducted an interdisciplinary project to address these knowledge gaps.

First, I advanced our understanding of the movement patterns and habitat use of skates by satellite tagging big skates in the GOA. The results show that big skates can, and likely frequently do, travel long distances, cross management boundaries within the GOA, and spend more time in deeper waters than previously thought. Second, I used the insights from the movement study to develop the first stock assessment models for skates in the GOA. This represents an important improvement in modeling, laying the groundwork for the North Pacific Fishery Management Council to move from Tier 5 (more data limited) to Tier 3 (less data limited) harvest control rules, which should lead to increased confidence with which the total allowable catch (TAC) for skates is set. Finally, I used the sustainable harvest estimates from the stock assessment models to develop a model that examined the impacts of management decisions on the profitability of skate fishing.

My research provides essential information about these understudied fishes, helping to improve the sustainability and profitability of skate harvests. Incorporation of best available science regarding skate ecology, population dynamics, and bioeconomics into fishery management fosters more responsible development of skate fisheries, sustainable fishery revenues, and employment, and reduces the risk of overfishing, stock collapse, and prolonged fishery closures. It is my hope that fishery management agencies and the fishing industry make use of the new information and insights presented in this dissertation to work collaboratively towards the responsible development of skate fisheries.

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Acknowledgements

A dissertation is never accomplished alone, much less an interdisciplinary one. It will not be easy to adequately thank all of you who have contributed to this work, and taught me countless lessons along the way. But I will try nonetheless…

First, I need to acknowledge the support, motivation, and inspiration I received from the fishing industry in Alaska. I'd specifically like to thank Bill Bailey (Copper River Seafoods), Bill Gilbert (Trident Seafoods), and Julie Bonney (Alaska Groundfish Data Bank) for their time, interest, and insights. I would also like to thank the crews of all the survey and fishing vessels who contributed data for the different parts of this research, and the crews of the F/V Alaskan Leader, F/V Ocean Prowler, and R/V Solstice for their assistance in capturing and tagging skates. In addition, I'd like to acknowledge the help of Torie Baker, Quentin Fong, and all of the Alaska Sea Grant Marine Advisory Program (MAP) agents who work to facilitate collaboration and information sharing between industry and researchers.

I also worked closely with several fisheries management agencies, all of which were extremely helpful in gathering data and developing research ideas. The Alaska Department of Fish and Game (ADFG), specifically Mike Byerly, Maria Wessel, Chris Russ, and Elisa Russ, provided state-level data and contributed to the early development of the project. Likewise, Chris Lunsford at the National Marine Fisheries Service (NMFS), and Eric Soderlund and Tom Kong at the International Pacific Halibut Commission, shared skate catch data. ADFG and NMFS also provided in-kind support for the fieldwork portion of this project, allowing me to tag along on their research surveys. Specific thanks go to Chris Gburski at the Alaska Fisheries Science Center (AFSC) for providing ageing data on both skate species. I would also like to acknowledge the essential help by Shellene Hutter (ADFG) and Cathy Tide (NMFS) in providing skate price and landings data, respectively.

Olav Ormseth (AFSC) and Ian Taylor (Northwest Fisheries Science Center) were instrumental in the development of the stock assessment models. Ian Taylor provided a lot of guidance and instruction in the implementation of Stock Synthesis, and helped with the parameterization of the model. Olav Ormseth provided data to inform the model, input on the assumptions and parameter choice, and helped structure the final model so that it would be as useful as possible to fisheries managers.

I would also like to thank the staff at the Kodiak Seafood and Marine Science Center for their help with the nutritional content analyses, and the staff at the Alaska Department of Environmental Conservation for their help with the contaminant analyses. Alex Oliveira provided much guidance and support in the development and implementation of the chemical analyses, and Jackie Knue helped run the heavy metal analyses. Lara Horstmann at the University of Alaska Fairbanks (UAF) provided essential guidance and instrument time to measure the nitrogen and protein content of skate tissues.

Funding for this project was received from Alaska Sea Grant (UAF grant #338152) with funds from the National Oceanic and Atmospheric Administration Office of Sea Grant, Department of Commerce, under grant no. NA14OAR4170079 (project no. R/32-05). This research was also sponsored by the Rasmuson Fisheries Research Center (Rasmuson Foundation) through an award to UAF, and directly by UAF with funds appropriated by the state. My work was also supported by the Northern Gulf of Alaska Applied Research Award (UAF grants #337168 and #337886). Along with these sources of funding, I would like to acknowledge the valuable assistance of the College of Fisheries and Ocean Sciences (CFOS) who managed and implemented these grants.

The Marine Ecosystem Sustainability in the Arctic and Subarctic (MESAS) program, an Integrated Graduate Education and Research Traineeship (IGERT) implemented by the National Science Foundation (Award #DGE-0801720), also provided funding for my research. In addition, MESAS provided a community within which to engage in interdisciplinary research, and foster new and innovative ideas. I would like to thank my fellow MESAS graduate students for their friendship and engaging discussions, as well as Ginny Eckert for her leadership as Director.

Many people within CFOS and the Fisheries Department ensured that all the nuts and bolts of my graduate program ran smoothly. But I would specifically like to thank Christina Sutton and Mercedes Anderson in the Academics office, as well as Gabrielle Hazelton and Karl Wuoti in the Juneau office. Their responsiveness and helpfulness allowed me to spend less time on paperwork and more time concentrating on my research projects.

I was very fortunate to have a supportive and interested Graduate Committee to guide me through my dissertation. Kenneth J. Goldman (ADFG) and Cindy Tribuzio (NMFS) granted much needed access to state and federal resources and information. They also contributed significantly to Chapter 1 of my dissertation. Gordon Kruse (UAF) and Keith Criddle (UAF) were excellent instructors and mentors, and contributed significantly to Chapters 2 and 3, respectively. All Committee members provided many helpful and constructive comments that improved my dissertation greatly. I also appreciate that they were understanding and supportive of other activities and side projects in which I wanted to engage, such as teaching and participating in the Knauss Marine Policy Fellowship.

Of course, I would like to extend an enormous thank you to my advisor, Andy Seitz. I am extremely grateful for his support and confidence throughout my time at UAF. He provided me with resources and opportunities, and a critical eye on my work and ideas. Andy gave me the tools to survive not only life in academia but also life in Alaska, and he always showed me how important it was to strike a good work-life balance. Those intense Chitina dipnetting missions for salmon were some of the most memorable and productive experiences I had in Alaska.

Also important to my happiness and sanity during this time were my labmates and friends. There are too many of you to list, but you know who you are. Thank you all for making my time in Alaska the most exciting, extreme, and enjoyable time I've spent on this earth. I was also given the opportunity in this time to be a volunteer firefighter and emergency medical technician for the Ester Volunteer Fire Department. This experience not only taught me a whole different set of skills, but also gave me a much-needed outlet for my non-academic energy. Thank you all for your continued service and sacrifice.

My parents, Claude and Maryvonne, and my brother, Mathieu, deserve enormous credit for their unwavering encouragement and love. Thank you for always pushing me to finish what I start, no matter how long it takes me.

Finally, to Megan – I could not have done this without your support, your love, and your patience. I truly appreciate all the help you have given me over the years, and along with Kaia and Annapurna, you have kept me sane, focused, and happy. You are Alaska to me, and I can't wait to enjoy non-grad student life with you.

Dedication

"Far and away the best prize that life has to offer is the chance to work hard at work worth doing." – Theodore Roosevelt (Labor Day speech, September 7, 1903)

To the hardworking Alaskan men and women of the fishing industry;

To the equally hardworking fisheries scientists and managers;

And to their continued productive, beneficial relationship;

May it persist evermore to ensure the long-term
sustainability of knowledge, livelihood,
and the last source of wild food.

General Introduction

Skates are dorsoventrally compressed cartilaginous fishes related to sharks and rays (subclass Elasmobranchii). Although the overall taxonomy of elasmobranchs is still being elucidated (see the ongoing work at sharksrays.org), it is generally accepted that all batoids (i.e., skates, rays, guitarfishes and sawfishes) are more closely related to each other than to other sharks (Nelson 2006). The classic view groups all batoids into one order, Rajiformes (Shirai 1996; de Carvalho 1996); but more recent work using morphological and molecular genetic data suggests three orders, including Rajiformes, Torpediformes and Myliobatiformes (Aschliman et al. 2012). Within Rajiformes, these authors suggest one family, Rajidae, which includes all skate species, although this is also contentious with some authors suggesting between two and four families (van der Laan et al. 2014).

Regardless of the number of families in which they are placed, over 280 skate species exist around the world (Nelson 2006), making it the most numerous elasmobranch taxon (Eschmeyer and Fricke 2013). Despite this relatively high species richness within elasmobranchs, skates are surprisingly uniform morphologically and ecologically (Bizzarro et al. 2014). All skates are benthic meso- or upper-trophic level predators (Ebert and Bizzarro 2007), oviparous (i.e., they lay egg cases, colloquially called mermaid purses), and inhabit temperate to polar regions of the world, from intertidal to abyssal depths (Ebert and Compagno 2007). However, some interesting biological variations exist within skates. For example, though almost all skates deposit egg cases on the seafloor with just one embryo inside, two species inhabiting the northern Pacific Ocean are known to include between two and eight embryos within one very large egg case (Ishihara et al. 2012). This fact prompted Ishihara et al. (2012) to suggest these two species, the mottled skate (formerly *Raja pulchra*) and the big skate (formerly *Raja binoculata*), be placed within their own genus *Beringraja*.

As a member of the larger subclass Elasmobranchii, skates share many physiological, biological, and ecological characteristics with sharks. One of their most relevant characteristics related to conservation is the low intrinsic rate of population growth exhibited by many elasmobranch species (Dulvy and Forrest 2010), due mainly to their slow growth rates, late maturation, and long gestation period (Cortés 2000). This makes many elasmobranchs, including skates, particularly sensitive to overfishing and puts them at risk of extirpation or extinction (Dulvy et al. 2014).

In addition to habitat loss, which may be of greater conservation concern for other batoids, such as sawfish of the family Pristidae (Harrison and Dulvy 2014), fishing mortality is the primary cause of population declines in skates (Dulvy and Reynolds 2002). In the northern Atlantic Ocean, where there is a long history of fishing for skates, many, but not all, species have suffered population decreases due to exploitation (Dulvy et al. 2014). Body size seems to influence the response of skate species to fishing mortality, with larger-bodied skates being more susceptible to population declines. For example, in waters off Europe, the common skate (*Dipturus batis*), the largest skate species in the world, has been extirpated from most of the North because of fishing (Walker and Hislop 1998). In contrast, some of the smaller skate species show increasing population size trends with exploitation (Rogers and Ellis 2000; Reynolds et al. 2005).

Though directed fisheries occasionally target[1] skates, they are most frequently captured incidental to other groundfish fisheries (Haas 2009). Bycatch is characterized as the unintentional capture of certain size classes, sexes or species of fishes while fishing for one or more target species (Alverson et al. 1994). Unintentional capture presents a pressing conservation concern that is distinct from concerns about directed fishing: bycatch species are by definition not attributed to the costs of fishing trips, which are usually attributed to the target species. As such, bycatch species will continue to be captured as long as the marginal revenue of catch of all species is greater than the marginal cost of fishing; there may not be any economic extinction prior to biological extinction (Roberts and Hawkins 1999). For example, on the U.S. east coast, the thorny skate (*Amblyraja radiata*) has recently been listed as a species of concern because of a long history of being captured as bycatch (NOAA 2012). The sharp decline in barndoor skate (*Dipturus laevis*) populations in the Atlantic Ocean was also attributed to overfishing, though the source of this harvest was both directed and bycatch (Casey and Myers 1998). More recent work on their population dynamics suggests that this species is less vulnerable to exploitation than previously thought (Gedamke et al. 2009). Nevertheless, retention of barndoor, thorny skates and one additional species, the smooth skate (*Malacoraja senta*), is currently prohibited in the U.S. federal directed skate fishery.

Management of mixed species fisheries is challenging, and may lead to either ecological costs in terms of fishing mortality (both retained catch and discard mortality of released catch) or economic costs to the fishery through increased costs associated with changes in

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[1] NOAA Fisheries defines target species as: "Those species primarily sought by the fishermen in a particular fishery. The subject of directed fishing effort in a fishery. There may be primary as well as secondary target species." (NOAA Fisheries glossary, https://www.st.nmfs.noaa.gov/st4/documents/FishGlossary.pdf)

fishing location, gear, or fishing practices; foregone revenue on discards; and unrealized catch of other species in the mixed species fishery. Common strategies to reduce ecological costs are: 1) setting season, area, or gear restrictions to reduce the likelihood of catching species of concern in the mixed species fishery; 2) setting and enforcing a total allowable catch (TAC) on each species encountered in a mixed species fishery; 3) placing retention trip limits or rate limits on particular species within the mixed species fishery; or 4) setting and enforcing individual or cooperative catch shares, as in U.S. West coast groundfish fisheries (PFMC and NMFS 2010), or deemed values, as in New Zealand (Peacey 2002), for each species in the mixed species fishery. To be efficacious, the first of these approaches requires a high level of predictability about when and where each species is likely to be encountered. The latter three approaches require accurate accounting for all species retained or discarded through some version of a catch accounting system (e.g., fisheries observers, video monitoring, audited logbooks). For example, early efforts to control catch of Chinook salmon (*Oncorhynchus tshawytscha*) in the Bering Sea/Aleutian Islands (BSAI) pelagic trawl fisheries entailed time-area closures. These proved ineffectual because the spatial-temporal distribution of Chinook salmon was unpredictable. In contrast, trawl bans in portions of the eastern Bering Sea (EBS) have succeeded in reducing catch of red king crab (*Paralithodes camtschaticus*) in pelagic and non-pelagic trawl fisheries. Setting and enforcing an overall bycatch cap has additionally been used to limit the total catch of Pacific halibut (*Hippoglossus stenolepis*) in the EBS bottom trawl fishery, often at the cost of substantial underharvest of the TAC of yellowfin sole (*Limanda aspera*), rock sole (*Lepidopsetta polyxystra*), and Pacific cod (*Gadus macrocephalus*). Similarly, in the northeast U.S., the skate complex is managed by setting total allowable landings for skates every year (NEFSC 2011). However, this approach can lead to rapidly attaining the allowable amount of some species and closure of the fishery before attainment of the TAC of other species in this mixed species fishery (Holland 2010), leading to economic inefficiencies (Abbott and Wilen 2009).

About 15 species of skates reside in the North Pacific, spanning all depths from the nearshore subtidal to the abyss. Currently in the Gulf of Alaska (GOA), skates are often retained when they are captured in groundfish fisheries, which primarily harvest a variety of demersal Osteichthyes (e.g., Pacific cod, Pacific halibut, sablefish *Anoplopoma fimbria*, Alaska pollock *Theragra chalcogramma*, and flatfishes). Skate stocks off Alaska are not considered to be overfished (that is, the estimated biomass is not less than one-half of the biomass corresponding to maximum sustainable yield, MSY), nor are they considered to be subject to overfishing (that is, being fished at a rate that exceeds the fishing mortality at MSY, F_{MSY}); however, thus far, there has been considerable uncertainty about skate population size, demographic parameters, and stock dynamics. They have thus been managed under a harvest control rule structured for poorly understood stocks (NOAA 2012). Given their healthy status, the Alaska Department of Commerce, Community and Economic Development encouraged the development of skate fisheries in Alaska in the future (ADCCED 2009). Of the 15 species of skates common to Alaskan waters, the big skate (*Beringraja binoculata*) and longnose skate (*Raja rhina*) grow to the largest sizes (Eschmeyer et al. 1983) and are the most commonly captured species in the GOA (Ormseth 2016a). Together, big and longnose skate landings averaged 3,138 metric tons (mt) per year between 2005 and 2016, representing 68.5% of annual skate landings from the GOA.

Beyond non-target captures, two attempts at targeted skate fishing were made in the last 15 years. In 2003, a directed fishery for skates developed around Kodiak Island, AK, when ex-vessel prices for skates increased from about US$0.20/kg to US$ 0.55/kg, matching the unit price for Pacific cod (Ormseth and Matta 2009). The directed federal waters fishery was closed in 2005 over concerns about the limited biological information on skates, the sudden increase in catches and potential risk of overfishing. However, non-target retention rates of skates have remained high since 2005 as ex-vessel prices continued to increase (Stevenson and Lewis 2010).

A second experimental directed longline fishery for big and longnose skates was opened in the State of Alaska waters of Prince William Sound (PWS) in 2009 and 2010. This opening was in response to requests by members of the local fishing community (Dr. Kenneth J. Goldman, Alaska Department of Fish and Game, Homer, pers. comm.) who felt that there was a market for skates and wanted to diversify into additional target species during the relatively slow winter/early spring season. In 2009, nine vessels participated in the experimental fishery, earning total gross ex-vessel revenues of US$64,590, assuming an ex-vessel price of US$0.55/kg (Stevenson and Lewis 2010). However, the fishery was closed after only eight days, as harvest of big skates vastly exceeded the guideline harvest level (GHL), due to an archetypical race-for-catch. In 2010, Alaska Department of Fish and Game (ADFG) instituted a trip limit of 1,133 kg (2,500 lbs) per two-day period, which resulted in decreased participation to six vessels, grossing a total of US$26,127. In 2010, fishing effort was concentrated closer to shore as the trip limit prevented revenues from offsetting the fuel costs of longer trips. With the added trip limit, the fishery was seen as being less profitable, and fishers abandoned targeting skates to take part in the U.S. federal

Pacific cod longline fishery, through which they could still retain skates as non-target catch. After the 2010 season, the PWS directed skate fishery was discontinued because of concerns about the sustainability of skate catches (Wessel et al. 2014).

Despite these two closures of directed fisheries, there remains an interest in developing a directed skate fishery in State waters of the GOA. Informal surveys in the Alaskan fishing communities of Cordova and Kodiak suggest that fishers view skates as abundant and a good source of additional revenue (Julie Bonney, Alaska Groundfish Data Bank, Kodiak, pers. comm.). Harvesters are confident that processors will continue to purchase skates that they land, and processors are willing to receive skates because there is demand from buyers in Asian export markets (Bill Bailey, President, Copper River Seafoods, Cordova, pers. comm.). Due to the steady rise in skate prices over the last 20 years, the fishing industry has continued to ask for increased fishing opportunities. Increased skate landings through additional retention of non-target skate catch or the development of a new directed skate fishery would expand revenues to fishers and processors and may contribute to the overall resilience of coastal communities by expanding fishing opportunities to additional seasons or increasing the value of fishing trips.

However, lack of knowledge about skates in the GOA and the increasing skate landings has led to a management response to curtail skate harvest rates. All bycatch, including skates, was restricted to a 20% maximum retainable amount (MRA) through 2015, meaning that skate bycatch could constitute up to 20% of the target species landings on any given trip. Starting in 2016, this MRA was reduced to 5% specifically for skates (NMFS 2015). Whereas before a harvester could land 200 kg of skates for every 1,000 kg of other target species (e.g., Pacific cod), they can now retain only 50 kg of skates for each 1,000 kg of a target species. While this measure may reduce retention and landings of skates, it likely will not lead to changes in the number of skates hooked or the total fishing mortality, when discard mortality is considered. Indeed, a restrictive MRA may increase discards, leading to an increase in fishing mortality, and could lead to forgone revenue for fishers and fish processors.

The two management agencies in charge of regulating skate fishing in the GOA, the National Marine Fisheries Service (NMFS) and ADFG have expressed a need for information about the ecology and population dynamics of skates (NPFMC 2010). In federal waters, skates in the GOA are managed under a Tier 5 harvest control rule as described in the GOA groundfish fishery management plan (FMP), a tier in which the only available information for setting catch specifications include estimates of biomass and natural mortality rate. Quotas are set based on extrapolated survey abundance estimates multiplied by an estimate of natural mortality and adjusted using a precautionary factor (Ormseth 2016a). This approach is intended to be conservative to account for the uncertainty associated with the low level of information (NMFS 2004). The Alaska skate (*Bathyraja parmifera*) is one of the more studied skates in the Bering Sea, and as a result is managed there pursuant to a Tier 3 harvest control rule (under the BSAI groundfish FMP) using parameters estimated through an age-structured model of stock dynamics (Ormseth 2016b). In Tier 3, fishing mortality is set based on reliable point estimates of biomass and fishing mortality reference points, which produces quotas that have more certainty and are more likely to avoid stock depletion (DiCosimo et al. 2010). With additional data collection and analysis, big and longnose skates in the GOA might likewise be managed under Tier 3 of the GOA groundfish FMP.

Over the last decade, data about skates in the GOA have been slowly accumulated. For instance, recent research has examined the maturity and reproductive biology of big and longnose skates (Ebert et al. 2008) and age and growth patterns of skates in waters off British Columbia (McFarlane and King 2006) and Alaska (Gburski et al. 2007). Studies on diet (Bizzarro et al. 2007; Ormseth 2011), thermal niche (Bizzarro et al. 2014), and depth occupancy (Love et al. 2005; Ormseth 2011; Stevenson et al. 2008) have also been published. However, these results have not been synthesized to provide for specific management actions.

In this dissertation, I draw upon recent research and apply new knowledge about skate biology and ecology in the GOA to model skate population dynamics and consider the bioeconomics of the fishery. Specifically, by focusing on the two most commonly landed skate species in the GOA, the big and longnose skate, I fill knowledge gaps by taking an interdisciplinary approach through three research chapters. In the first chapter, I advance our understanding of the movement patterns and habitat use of big skates through satellite tags, with a discussion about population structure throughout the GOA. The second chapter incorporates these data into a stock synthesis modeling framework to inform the development of the first population dynamics models for big and longnose skates in the GOA. Finally, the third chapter presents a bioeconomic model that examines the impacts of management decisions on the profitability of skate fishing. My research provides essential information about these understudied fishes, endeavoring to improve the sustainability and profitability of skate harvests.

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Chapter 1: First Use of Satellite Tags to Examine Movement and Habitat Use of Big Skates (*Beringraja binoculata*) in the Gulf of Alaska[2]

1.1 Abstract

Big skate (*Beringraja binoculata*) is the most frequently landed skate in the Gulf of Alaska portion of the Northeast Pacific Ocean, with recent stock assessment surveys showing relatively healthy skate stocks and continued interest from the commercial fishing industry to increase skate landings. Considered a data-poor species, there is a need for additional ecological information on big skates, including movement patterns and habitat use. We deployed pop-up satellite archival transmitting (PSAT) tags on eight big skates in the Gulf of Alaska and set the tags to release one year after deployment. The minimum distance traveled by big skates varied between 6 and 205 km, with one individual traveling at least 2100 km based on light geolocation data. Three individuals showed evidence of having made long-range movement and crossed at least one management boundary, and three remained relatively close to their tagging locations. Two tags did not report. The PSAT tags also extended the maximum documented depth of big skates to over 500 m, and confirmed that they are thermally tolerant, occupying waters between 2° and 18°C. Because the total catch of big skate is divided into multiple areas and limited movement between areas is assumed, information from this study will aid in the development of appropriate spatial management plans for this species.

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1.2 Introduction

Skates (Rajiformes: Rajoidei) are dorsoventrally compressed cartilaginous fishes related to sharks and rays and are increasingly recognized as an important part of the benthic ecosystem (Coll et al. 2013). They are captured in directed fisheries and retained in other fisheries as non-targeted catch, mainly for their pectoral fins or "wings". Recently, there has been interest in further developing skate fisheries in Alaska (ADCCED 2009), where skate stocks are not currently listed as overfished or threatened by overfishing (NMFS 2013). Of the 15 most common species of skates captured in the Gulf of Alaska (GOA), the big skate (*Beringraja binoculata*, formerly *Raja binoculata*) is the largest (Eschmeyer et al. 1983) and most frequently retained species in state and federal waters (Ormseth 2015). The North Pacific Fishery Management Council, the management body responsible for federal fisheries management in the exclusive economic zone (3 – 200 nmi) off Alaska, currently treats big skates as a data-poor species. It has designated skates as a research priority and determined that stock assessment and management of data-poor stocks, such as skates, requires basic life history information and better estimation of fishery interactions (NPFMC 2015). Likewise, the Alaska Department of Fish and Game recognizes the important role of big skates in coastal ecosystems and as a species captured in state-managed fisheries within 3 nmi of the coast, and therefore seeks to collect more biological and ecological information about this species (Wessel et al. 2014).

The knowledge base of big skates has been growing over the past decade, including studies on diet (Bizzarro et al. 2007; Ormseth 2011), age and growth (McFarlane and King 2006; Gburski et al. 2007), reproductive biology (Ebert et al. 2008), and distribution (Stevenson et al. 2008; Bizzarro et al. 2014). In the GOA, big skates aggregate in certain "hot spots" along the coast of Alaska (Bizzarro et al. 2014). Most studies indicate that big skates primarily occupy depths between the surface and 200 m (Love et al. 2005; Ormseth 2011), although bottom trawl surveys have retrieved big skates from hauls occurring as deep as 376 m in Alaska (Stevenson et al. 2008), and 459 m along the west coast of the U.S. (Bizzarro and Summers 2015). Big skates are also considered to have a wide thermal niche (Bizzarro et al. 2014).

However, there have been no studies to identify habitat use (such as depth and temperature occupancy). One study has examined movement of big skates in the Pacific Ocean using conventional tags in waters off British Columbia, Canada (King and McFarlane 2010). In that study, over 18,000 big skates were tagged, of which 17 traveled between 800 and 2,370 km and were recaptured in the GOA, the Aleutian Islands, or the Bering Sea. However, about 75% of these tagged big skates were recaptured within 21 km of the release location by the commercial fishing fleet, indicating that the majority of skates may not undergo long-distance movements. Whereas conventional tagging efforts are informative, they rely on recaptures in commercial fisheries, which in turn depend on temporal and geographic coverage of fishing fleets (Bolle et al. 2005). Consequently, conclusions regarding movement and distribution of fishes may be biased by unequal spatial and temporal commercial fishing efforts. Moreover, conventional tags do not provide information about movement or habitat utilization by tagged fish while at liberty. Lacking information to the contrary, management agencies assume that big skates do not make extensive movements or cross management boundaries and that they are restricted to relatively shallow waters where fishing occurs.

Satellite tagging provides a fisheries-independent solution for examining movement patterns and habitat use of big skates in the GOA region. Pop-up satellite archival transmitting (PSAT) tags measure and record temperature, depth, and ambient light data at user-specified intervals while externally attached to the fish (Arnold and Dewar 2001). On a user-programmable date, the tag releases from the fish, floats to the surface of the ocean, and transmits summarized data to orbiting satellites such as the Argos satellite system. PSAT tags do not need to be physically recovered and are therefore a fisheries-independent means of studying fishes, and a valuable tool for studying the biology and ecology of elasmobranchs (Conrath and Musick 2008; Weng et al. 2008), as well as other benthic species, such as Pacific halibut (*Hippoglossus stenolepis*) (Seitz et al. 2003; Loher and Seitz 2006).

This study provides the first documentation of the movement, swimming depth, and ambient temperature occupancy for big skates in the GOA. Based on previous studies, we hypothesized that no more than 25% of tagged skates moved beyond the area where they were tagged, that big skates occupied depths up to 500 m, and that they utilized a wide temperature range. Although the information from PSAT tags may not be easily extrapolated to populations, it can be used to determine how far individuals are able to travel and what temperatures and depths they can tolerate and may prefer, independent of fishing effort. Results from this research will help advance our understanding of the biology and ecology of big skates and will be valuable in the evaluation of assumptions currently made in stock assessment models used for managing fisheries in the GOA.

1.3 Materials and Methods

1.3.1 Study area and skate collection

Eight big skates were captured in the State of Alaska waters of Prince William Sound (PWS; n = 7) and the U.S. federal waters of the continental shelf (n = 1), of the GOA (Figure 1.1A). Alaska state waters, including all of PWS, are managed by the Alaska Department of Fish and Game. U.S. federal waters are managed by the National Marine Fisheries Service (NMFS), which divides the federal waters of the GOA into the western GOA (WGOA), central GOA (CGOA), and eastern GOA (EGOA; Figure 1.1), each with its own allowable biological catch and overfishing level.

PWS is a large (> 9,000 km^2) productive fjord estuary with seasonally high freshwater input from surrounding glaciers and precipitation runoff (Stabeno et al. 2004; Harwell et al. 2010; Musgrave et al. 2013). Due to this seasonal melt, mean surface temperatures range from 4° to 13°C, while bottom temperatures range from 4° to 7°C (Vaughan et al. 2001; Musgrave et al. 2013). The bathymetry of PWS is complex, with many islands and steep slopes dropping to 800 m over short distances. Surface circulation in PWS changes seasonally, being a relatively closed system during the spring and summer, while southerly flows in the autumn and winter exit PWS through its two main connections to the GOA, both of which have sills shallower than 200 m depth (Harwell et al. 2010; Musgrave et al. 2013). Water temperatures near the surface in GOA vary seasonally from 3.5° to 13°C, whereas they are fairly constant around 6°C near the seafloor. The continental shelf can be as narrow as 5 km in Southeast Alaska to more than 200 km wide around Kodiak Island, Alaska, and varies in depth between 150 and 250 m, after which the continental slope descends rapidly to abyssal depths of 4000 m (Weingartner 2007).

In PWS, big skates were collected 5 – 14 July 2011 during the Alaska Department of Fish and Game multi-species large mesh bottom trawl survey. The trawls were conducted during daylight hours for approximately 26 minutes, covering a distance of 1.85 km at depths between 0 and 500 m, following standardized agency methods (Rumble et al. 2014). The big skate tagged in U.S. federal waters was collected on 25 August 2013 during the annual NMFS longline survey, which covered over 16 km of groundline deployed down the continental slope and left to soak for 4 to 8 hours at each station, following standardized NMFS methods (Lunsford and Rodgveller 2013). The University of Alaska Fairbanks Institutional Animal Care and Use Committee (IACUC) has approved the collection and tagging of big skates under UAF IACUC Protocol #217575 (Appendix C).

1.3.2 PSAT tag attachment and deployment

Immediately after bringing the skates on deck, they were placed in a 1 m x 2 m x 1 m (length x width x depth) holding tank equipped with flowing seawater for at least 10 minutes to recover. They were then weighed to the nearest 0.1 kg, measured to the nearest 1 cm (total length, TL, from tip of the snout to the tip of the tail measured in a straight line, and disc width, DW, from one wing tip to the other, measured in a straight line), and sexed based on the presence or absence of claspers. Males were also assessed for maturity using clasper length and calcification (Ebert et al. 2008). We only tagged big skates that displayed regular spiracle breathing, had no visible wounds, and were larger than 8 kg (corresponding to approximately 100 cm TL). This size was selected based on an analysis of the drag caused by PSAT tags attached to cownose rays (*Rhinoptera bonasus*) over 7.8 kg, showing they could carry a PSAT tag at moderate speeds with an extra energy exertion of only about 5% (Grusha and Patterson 2005). Because of the similar body shape and swimming mode shared by cownose rays and big skates, a big skate larger than 8 kg was assumed to be able to carry a PSAT tag with minimal effects on its swimming efficiency.

Skates were tagged with Mk10 PSAT tags (Wildlife Computers, Inc. Redmond, WA), measuring 175 mm in length, 40 mm in diameter and weighing 75 g in air and pressure rated to 2,000 m. The attachment system was based on one developed for Pacific halibut (Seitz et al. 2003), consisting of a titanium dart that was connected to the corrodible link of the PSAT tag with a short length (15 cm) of monofilament fishing line (250 lb. test) covered with heat shrink plastic tubing to minimize abrasion to the skin of the skate (Seitz et al. 2003). Immediately before tag deployment, the dart and tether were disinfected with 95% ethanol. To attach the tag, the dart was inserted into the wing of a big skate dorsoventrally, midway between the eye orbit and the insertion of the pectoral fin, and one-third the distance between the spine and the wing tip (Figure 1.2). The dart was pushed through the pectoral radials so that it locked in the radials, immediately above the skin on the ventral side of the skate. Total measuring and tagging time for each skate was less than 10 min, with skates being out of water for a maximum of 2 min at a time. The skates were not anesthetized during the process (UAF IACUC protocol #217575, Appendix C).

Once tagged, the skates were immediately released back into the ocean as close to the site of capture as possible (between 0 and 2 km). Release of tagged big skates in state waters was accomplished by placing the individual in a 1 m by 1 m square of netting attached to four lines. While the trawl vessel was stationary, the net was lowered in the water and left in place until the skate voluntarily exited the net (Figure 1.2). In federal waters, the tagged skate was released by hand over the side of the longline vessel and observed until it swam out of sight.

1.3.3 Data collection

The tags were programmed to collect three types of data at 5-s intervals: depth (range: -40 to 1000 m, resolution: 0.5 m), ambient water temperature (range: -40 to 60° C, resolution: 0.05° C) and ambient light intensity (sensitivity: 5×10^{-12} to 5×10^{-2} W/cm^2). For tags deployed in 2011, the archived depth and temperature data were summarized into 4-hr bins (00:00 – 03:59, 04:00 – 7:59, etc.) for transmission to satellites. For each time bin, the tag transmitted data representing the percent of time the tag spent in each of nine temperature bins (< 0° C, [0 – 2[, [2 – 4[, [4 – 6[, [6 – 8[, [8 – 10[, [10 – 14[, [14 – 18], > 18) and eleven depth bins (< -1 m, [-1 – 25[, [25 – 50[, [50 – 75[, [75 – 100[, [100 – 125[, [125 – 150[, [150 – 175[, [175 – 200[, [200 – 500], > 500 m). More depth bins were created between 0 and 200 m because big skates were expected to spend the majority of their time in shallower waters. Satellite transmissions of tag data also included daily maximum and minimum temperatures and depths. One tag was physically recovered, and the complete archived 5-sec interval data set was retrieved. It was sent back to the manufacturer, refurbished, and re-deployed on a big skate in 2013 in the GOA (Table 1.1). The refurbished tag was programmed slightly differently because general habitat use data had already been acquired with the first round of tagging. Instead of binning depth and temperature data, it was programmed to collect time-series data of the ambient water temperature and depth at 10-min intervals. In both years, ambient light intensity data collected by the tags were processed by the onboard computer to produce light curves for sunrise and sunset each day.

All PSAT tags were programmed to release 323 to 365 days after deployment to provide approximately one year of data and release during the summer months when more fishing vessels are present to increase the likelihood of recovering the tags. The tag's programming sent a small electrical signal through the corrodible wires attaching the tags to the skates, causing them to corrode. The PSAT tags then released from the skates, leaving behind only the dart tags. After releasing, the slightly positively buoyant PSAT tags floated to the surface and transmitted the summarized data and light curves to the Argos satellite system. The surface locations of the tags were determined from the Doppler shift of the radio frequency transmitted in successive uplinks received during one Argos satellite pass (Keating 1995). The first location for each tag with an Argos class of 1, 2, or 3 (indicating an accuracy <1.5 km) was considered the end location of that skate track. Summarized depth and temperature data, and light curves produced from ambient light intensity data, were downloaded from the Argos satellite system data servers.

1.3.4 Data analysis

Tag transmission performance was assessed to examine the representativeness of each tag's data record for describing each skate's behavior and environment during its entire time at-liberty. Tag transmission performance was defined as the proportion of data retrieved by Argos satellites from each transmitting tag, and was calculated by dividing the number of data packets retrieved by Argos by the hypothetical number of packets the tag could have transmitted under ideal conditions. The hypothetical number of packets depended on the duration of tag deployment and the number of data summaries per day.

To investigate the movement of skates while at liberty, the minimum horizontal movement was calculated as the shortest great-circle distance between the tagging and end locations, allowing for this distance to pass over land. In addition, light-based geolocation was used to examine whether skates travelled farther while at liberty than might be shown by their release and end locations alone. Longitude estimates are usually more accurate than latitude estimates for approximating positions of demersal fishes (Seitz et al. 2006), so we focused our analyses on the longitude estimates alone. To obtain longitude estimates, the downloaded light curve data were processed by Wildlife Computer's proprietary Data Analysis Program (DAP; Wildlife Computers, Redmond, USA), which estimated times of sunrise/sunset and local noon, followed by the Global Position Estimator (GPE-2; Wildlife Computers, Redmond, USA), which calculated the longitude. These light-based longitude geolocations were examined visually by assessing the slope of the light curve for both dawn and dusk (Seitz et al. 2006). Poor light curves (asymmetrical dawn and dusk curves and/or very shallow slopes in the curve) and highly uncertain positions were discarded. Each longitude estimate was associated with a measure of uncertainty based on the quality of the light curve, and the longitude estimates of a tag, along with the uncertainty estimates, provided a measure of the east-west movement of the tagged skate. We considered applying filters to improve these position estimates; however these filters are primarily based on environmental variables, which either do not apply to skates (e.g., sea surface temperature), or for which sufficient data are not available (e.g., bottom temperature).

The movement of skates could have management implications if skates moved frequently between management areas. Since each area has its own catch limit, biomass transferring from one area to another could influence the proportion of the stock that is available to harvest in those areas. To infer whether skates crossed management boundaries, we examined the end locations, light-based longitude estimates, and temperature and depth records. The management areas in the GOA are mostly oriented east to west, meaning that changes in light-based longitude estimates can be used to infer movement between management areas, as seen in several Pacific halibut studies (Seitz et al. 2003; Loher and Seitz 2006; Loher 2008; Loher and Blood 2009; Seitz et al. 2011). A skate was considered to have crossed a management boundary if the longitude estimates crossed the longitudinal boundary of the management area, and the uncertainty range did not overlap with the management boundary. In addition, different management areas (i.e., PWS vs. the central GOA shelf) have different temperature-at-depth characteristics, so the entire depth and temperature records from the one physically recovered tag were examined to provide coarse inference on whether the skate moved between these different bodies of water.

Finally, to examine seasonal depths and water temperatures occupied by tagged big skates, data from both satellite transmissions and the physically recovered tag were grouped into summer (July – September), autumn (October – December), winter (January – March), and spring (April – June) seasons. Differences in time spent in depth and temperature bins among seasons were analyzed using a chi-square test (Zar 1999).

All statistical analyses were conducted with R (R Core Team 2014), using a significance level of α=0.05. Mapping and distance measurements were performed in ArcGIS (v.10.2, ESRI, Redlands, USA). The depth and temperature plot of the recovered tag was produced with MatLab (v.R2014b, MathWorks, Inc.). For identification purposes, the tagged skates are identified in the figures and tables by a four-character code designating their sex and TL (e.g., M124 for a male skate measuring 124 cm TL).

1.4 Results

Five female and two male big skates (range 110 – 165 cm TL) were captured and tagged between 49 and 190 m water depth in the eastern part of PWS in 2011 (Table 1.1). The tag deployed on a 164 cm TL female was recovered on a beach by a commercial fisherman and returned in 2012. After the full data set was downloaded, the tag was refurbished and re-deployed in 2013 on an eighth big skate, a 177 cm TL female captured at a depth of 205 m southwest of Kodiak Island (Figure 1.1).

1.4.1 Tag performance

Six of the eight PSAT tags deployed on big skates in the GOA reported to satellites upon pop-up whereas the other two failed to report (Table 1.1). Of these, five transmitted 69% to 99% of their summarized depth, temperature and light level data. The sixth tag (F165) reported its final location through the Argos satellite system but did not transmit any other data (Table 1.1). The tag on F110 prematurely released after 90 days at liberty, but the other four tags remained attached nearly a full year. In all, we recovered a total of 931 days of depth data and 922 days of temperature data. While at liberty, the tags collected light level data, but only 31 to 62 acceptable daily light curves were produced per tag (Table 1.1).

1.4.2 Movement

The six tags for which Argos-calculated end locations were available popped up in three different management areas (Table 1.1). Four of the tags deployed in PWS had end locations in PWS (minimum horizontal movement 6 – 113 km) and one had an end location in the CGOA (minimum horizontal movement 205 km). The tag deployed in the CGOA transmitted its data from WGOA (minimum horizontal movement 278 km; Figure 1.1). The three tagged skates that moved a minimum of 100 km travelled to the southwest, whereas the other three travelled to the southeast and northeast while remaining in eastern PWS.

Of the five tags from which daily geolocation longitude estimates could be derived, two dispersal types were observed. The first dispersal type was defined as having start and end locations in the same management area and with no evidence that the tagged skates crossed management boundaries while they were at liberty (F145 and F110; Figure 1.3A). The second dispersal type was exhibited by three skates that crossed management boundaries while at liberty. In one case (F177), the light-based longitude estimates showed a direct westward progression from the point of release to the end location, undertaken primarily in the late summer and autumn. In another case (M124), the release and end locations were in relatively close proximity (205 km apart), but the longitude estimates provided evidence that the fish traveled much farther than the minimum horizontal distance between those two points. Indeed, the geolocation data suggest that this skate moved at least 2100 km from the release site in PWS (longitude 146.6°W), through the CGOA and into the WGOA to 160°W (±1°), between July 2011 and January 2012; and then the skate moved back to 149.3°W in the CGOA by May 2012 (Figure 1.3B). In doing so, the skate crossed three management boundaries in 314 days, for a minimum average speed of 6.8 km per day. Finally, evidence of this dispersal pattern was also found using the fine-scale data from the physically recovered tag (F164), which allowed a closer examination of the depth and temperature occupancy of this skate. The data from this tag suggest that the skate moved out of PWS and into the GOA in mid-August, and subsequently returned into PWS in late September. In PWS, the tag experienced water at 20 m depth that only reached 8°C in late July, and then as it moved into the GOA, it experienced temperatures above 10°C at 70 m in August and September 2011 (Figure 1.4). In addition, the maximum depth of the tag between mid-August and mid-September did not exceed 115 m, more typical of the depths on the continental shelf of the GOA. Starting in late September, the tag again experienced deep depths typical of PWS.

1.4.3 Depth and temperature range occupancy

Tagged big skates occupied depths from 0 to > 500 m and encountered temperatures between 2° and > 18°C (Figure 1.5). Based on depth and temperature occupancy, three depth-based behavior types were inferred: local resident, slope transient, and shelf transient. The local resident behavior type was demonstrated by skates that provided no evidence of long distance movement while tagged (F145 and F164). As mentioned earlier, F164 likely crossed a management boundary, from PWS to GOA, but based on its location, it did so while still undergoing a small (less than 100 km) horizontal movement (Figure 1.1). Local residents occupied different depth ranges in summer and winter, staying above 50 m for most of the summer, but spending most of the winter and spring between 100 and 200 m (Figure 1.5). Temperatures experienced by these skates were confined to between 4° and

14°C, although they primarily occupied waters between 10° and 14°C during the summer, and spent all of winter and spring almost exclusively in 4° to 6°C waters (Figure 1.5).

The skate for which we had fine-scale data (F164) experienced a maximum depth of 376 m, with an average of 125.6 m (± 60.96 m, 1 SD), and a temperature range between 3.2° and 12.9°C (average 6.2°C ± 2.09°C). Interestingly, despite its wide depth occupation, F164 spent 39.8% of its time at liberty in a 20-m depth range between 122 and 140 m. It returned to that depth range 12 times during the year, each time staying there more than 3 days consecutively (Figure 1.4). Often while in this depth range, the depth record changed in a sinusoidal fashion, exactly mirroring the tidal cycle in PWS. For example, during a 4-day bout in April 2012, the water depth of the skate tag and the tidal cycle were not significantly different in amplitude (paired t-test: t_6=0.95, p=0.38), cycle length (paired t-test: t_6=0.75, p=0.48), and timing (paired t-test: t_6=1.24, p=0.98). This suggests that the skate was stationary on the sea floor for 3 to 15 days at a time, while the water column height fluctuated with the tide.

The slope transient behavior type was associated with skates that traveled over 100 km; occupied shallow depths (<175 m) during the summer, spring and autumn; and occupied depths down to 500 m during the winter (i.e., M124, F110; Figure 1.5). Based on the longitude estimates while at liberty, it appears these skates undertook their long range movements in the late summer or early autumn (Figure 1.3). Although F110 was only at liberty for 90 days, it started displaying this long-range movement while spending over 84% of its time between 0 and 50 m in the summer and autumn. During the winter and spring, the slope transients occupied warmer waters (mostly 6° to 8°C) than the other two behavior types, and never occupied waters colder than 4°C (Figure 1.5).

The final depth-based behavior type, the shelf transient (F177), moved long distances along the continental shelf and never experienced depths below 150 m, most likely because it remained on the continental shelf throughout its time at liberty. In contrast with the other two depth-based behavior types, this skate occupied shallower depths more often in winter and spring than summer and autumn (Figure 1.5). The shelf transient behavior type generally occupied colder waters than the other behavior types, inhabiting mostly 4° to 6°C waters during the winter and spring. While dispersing in the summer and autumn, it mostly occupied a temperature range of 6° to 8°C.

1.5 Discussion

Satellite tags deployed on big skates provided novel ecological data, allowing insight into their behavior that can be used to help evaluate and potentially refine assumptions currently used in the management of this species. Specifically, we found that this species may undergo large horizontal movements and occupy greater depths more often than previously thought. Therefore, it is prudent to re-examine the assumption that big skates undergo limited long-range movements. Interestingly, the area around the Shumagin Islands in the WGOA, to which two tagged skates traveled, has been recently identified as a location with high spring and summer big skate abundance, based on trawl survey data spanning 1999 – 2012 (Bizzarro et al. 2014). In addition, both tagging locations were within a high abundance location identified by Bizzarro et al. (2014). Together, these findings suggest that there may be multiple areas around the GOA that have relatively high densities of big skates, at least during the spring and summer seasons, and that big skates may travel between them. In other words, these areas are not isolated hot spots or the centers of distinct big skate populations, but rather areas that may have seasonal characteristics beneficial to big skates, such as abundant food sources, protection from predators, optimal temperatures, or hold importance as nursery and mating areas.

Conventional tagging studies almost certainly underestimate the distance travelled and number of management boundaries crossed by skates. One skate in our study traveled a net distance of 21 km between tagging and end locations, but the archived data suggested a much larger scale movement. Data from another skate showed that tagging and end locations alone underestimated the distance traveled and the number of management boundaries crossed. A conventional tagging study in British Columbia found that only 6.1% of big skates were recaptured over 100 km from the tagging location, and that 70% of the skates that traveled over 800 km were females of immature size (King and McFarlane 2010). We found both males and females underwent long movements, and the longest movement (>2,000 km) was undertaken by a male of mature size. In the conventional tagging study, big skates traveled at an average speed of 2 to 6 km per day, similar to what we found in this study.

In contrast to the skates that traveled away from their tagging areas, three of the tagged skates (50%) likely remained in PWS for the duration of the tag deployment, and traveled a maximum of 21 km between tagging and pop-up locations. It is noteworthy that this is the same distance within which 75% of the big skates conventionally tagged in British Columbia were recaptured (King and McFarlane 2010). Site fidelity has been found in other electronic tagging studies of skates: common skates (*Dipturus batis*) in the North Atlantic (Wearmouth and Sims 2009) and Arctic skates (*Amblyraja hyperborean*) in the Canadian Arctic (Peklova et al. 2014). It has been proposed that persistent food supplies may account for site fidelity in some skates (Wearmouth and Sims 2009), and that high abundance locations for other species could be linked to niche differentiation between species (Bizzarro et al. 2014). In our study, we did confirm that big skates show site fidelity rather than inferring it based on the tagging and recapture location of conventional tags.

Consistent with findings in other studies (Love et al. 2005; Ormseth 2011), big skates tagged with satellite tags spent the majority of their time at depths ≤200 m. However, they also occupied greater depths more often than previously assumed (Stevenson et al. 2008), most likely as a result of limited coverage of surveys during the winter and spring when big skates occupy relatively deeper water. The maximum depth of big skates has occasionally been reported in the literature as 800 m, always citing the same unpublished manuscript (Howe 1981). This likely spurious record has not been confirmed as far as we can tell and should not be cited until confirmed. The deepest confirmed records of big skates are 376 m in the GOA (Stevenson et al. 2008) and 459 m along the California coast (Bizzarro and Summers 2015), both from summer bottom trawl surveys. Our study has not only confirmed that big skates can travel below 500 m, it has also shown that big skates occupy these greater depths more often than previously thought, with one individual spending nearly 10% of the winter season below 500 m. Ecological knowledge such as this provides evidence for extending the habitat description of big skates.

The temperature range occupied by big skates in this study is similar to that found in previous research (Bizzarro et al. 2014) and confirms that big skates are thermally tolerant, occupying temperatures between 2° and 18°C. Overall, tagged big skates in this study generally occupied deeper and colder waters during the winter and spring seasons. The temperature occupancy was most likely related to available water temperatures, which are usually restricted to between 4° and 7°C in both the GOA and PWS during the winter (Vaughan et al. 2001; Weingartner 2007; Musgrave et al. 2013). During the summer and autumn, when a stronger thermocline is established and a wider range of temperatures is available, the tagged skates tended to occupy warmer temperatures at shallower depths, possibly for the metabolic advantages conferred by warmer temperatures (Wallman and Bennett 2006). Temperature is an important factor in structuring skate assemblages (Arkhipkin et al. 2012; Bizzarro et al. 2014), parsing out the habitat between species based on their thermal optima. However, other factors, such as food availability may further refine this distribution; and a thermally tolerant species like the big skate may occupy sub-optimal temperatures to reduce competition if other skate species are present (Bizzarro et al. 2014).

PSAT tags deployed on big skates were able to provide novel and salient ecological information on a potentially important commercial fishery species, but this technology comes with a certain number of caveats and drawbacks. First, two tags (25% of deployed tags) did not report, and therefore there was no evidence of the reason for their lack of data transmission. This percentage of tag failure is comparable to other studies that have deployed PSAT tags on demersal, high-latitude species like Pacific halibut (19% tag failure; Seitz et al. 2011), Pacific sleeper shark *Somniosus pacificus* (33% tag failure; Hulbert et al. 2006), and Arctic skate (22% tag failure; Peklova et al. 2014). Despite these failures, successful big skate tags reported the majority of their data, providing us with valuable insight into the ecology of this species. Second, only six tags provided data, making any population-level extrapolations tenuous. Big skates likely display more than three behavior types, and our small sample size is not sufficient to define all behaviors that this species can exhibit. Although we were able to show that big skates are capable of long-range movements, understanding the frequency of this long-range movement at the population level will require a much larger sample of tagged individuals. Third, the size of the PSAT tags restricted us to use only larger individuals (over 100 cm TL) to avoid affecting their behavior, but there is conflicting evidence as to which way this might have biased our conclusions. Wearmouth and Sims (2009) determined that larger common skates were more likely to be vertically active, based on PSAT tag data. However, conventional tags on big skates in British Columbia showed that smaller (< 90 cm TL) individuals undertook most of the long-range movements (King and McFarlane 2010).

Finally, some of the capabilities of PSAT tags, namely the ability to determine geolocations based on ambient light levels, have increased error for a demersal species and at high latitudes. New models are being developed that may help refine positions of fish tagged in high latitude areas, such as the hidden Markov models (HMM) that integrate maximum depth, tidal patterns and activity of the fish (Pedersen et al. 2008). Most other existing models use a sea-surface temperature and/or primary productivity-based approach (Chittenden et al. 2013), which cannot be applied to deeper water demersal species like skates.

Although the present study only examined a small number of individuals during a relatively short time scale, the results provide initial qualitative evidence that big skates can, and likely frequently do, travel long distances, cross management boundaries within the GOA, and spend more time in deeper waters than previously thought, especially during the winter months. As a result, this information can be used to refine assumptions of stock assessment models, such as the depth selectivity of fishing and survey gear, the area of suitable skate habitat for extrapolating abundance surveys, and movement rates among and out of management areas. Managers may therefore want to consider incorporating catch rates at multiple depths during abundance surveys. Developing management strategies for this species at the scale of the entire GOA, rather than broken down into smaller management areas (such as WGOA, CGOA, and EGOA) may also warrant consideration. Future research should be designed to further quantify the connectivity of big skates across the entire GOA to better define their stock structure and to facilitate coordinated management in state and federal waters.

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Table 1.1. Deployment summary for pop-up satellite archival transmitting (PSAT) tags attached to big skates in the Gulf of Alaska (GOA). Table includes sex, total length (TL), disc width (DW), age, tagging and pop-off dates, location and management area, days at liberty and percent data that was reported to the satellite. The sex and TL are used to identify the skate.

Sex	TL cm	DW cm	Age[1] yrs	Tagging Date	Tagging Location		Tagging Area[2]	Pop-off Date	End Location		Pop-off Area[2]	Horiz. Mvt.[3]	Days at Liberty	Data Reported	# Light Locations
F	145	111	10	5 Jul '11	60.6194	-146.4038	PWS	23 Jun '12	60.692	-146.173	PWS	15 km	354	80%	31
F	165	133	13	5 Jul '11	60.4846	-146.6588	PWS	7 Jun '12	60.607	-146.366	PWS	21 km	338	0%	0
M	124	101	10	8 Jul '11	60.5595	-146.5758	PWS	17 May '12	59.327	-149.300	CGOA	205 km[4]	314	69%	44
F	164	126	13	9 Jul '11	60.5755	-146.3595	PWS	18 Jun '12	60.527	-146.303	PWS	6 km	345	89%	47
M	121	88	10	12 Jul '11	60.8153	-146.8493	PWS	-	-	-	-		-	0%	0
F	110	81	6	14 Jul '11	60.7347	-146.1065	PWS	12 Oct '12	60.152	-147.791	PWS	113 km	90	99%	62
F	157	117	12	14 Jul '11	60.6442	-145.6787	PWS	-	-	-	-		-	0%	0
F	177	134	15	25 Aug '13	56.1867	-155.9883	CGOA	1 Jun '14	54.775	-159.589	WGOA	278 km	280	72%	40

[1]Age based on the von Bertalanffy growth curve determined for GOA skates by Gburski et al. (2007).
[2]PWS = Prince William Sound, CGOA = Central Gulf of Alaska, WGOA = Western Gulf of Alaska.
[3]Horizontal movement is the shortest straight-line distance between the tagging and end location, and represents the minimum distance the skate could have traveled while at liberty.
[4]Based on light geolocation data, this skate actually traveled over 2000 km.

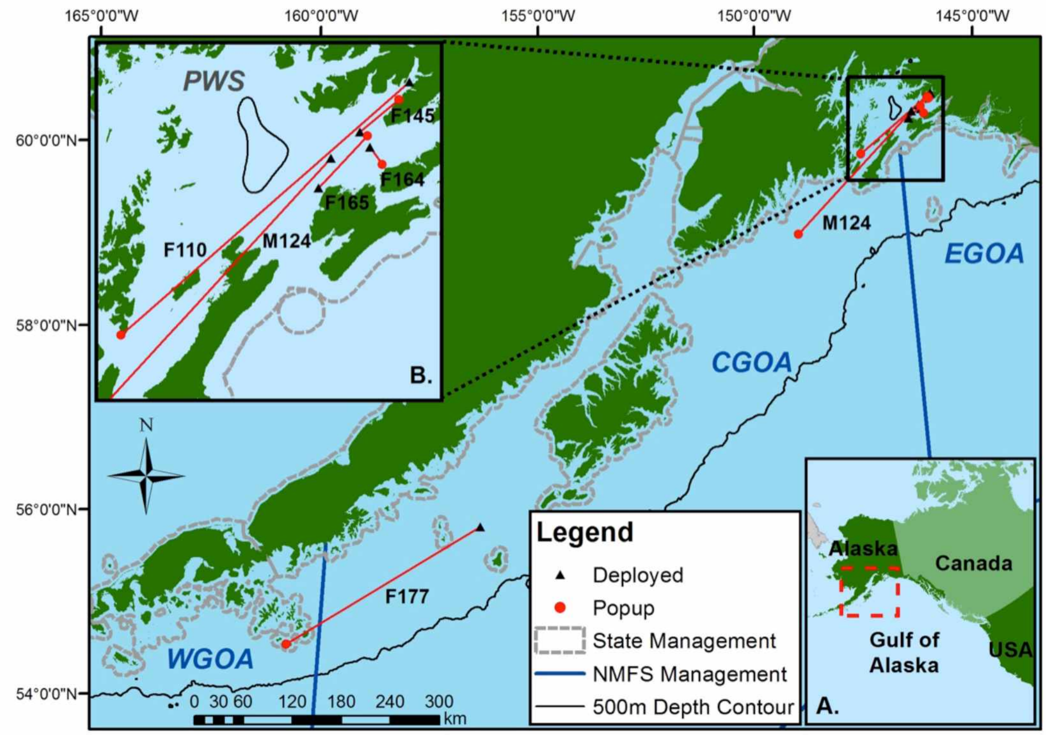


Figure 1.1. Deployment and end locations of tagged big skates in the Gulf of Alaska (GOA). Skates are designated by their sex and total length (e.g., F177 is the 177 cm female). Borders of the state management area (3 nmi) are shown in the grey dashed line, and the National Marine Fisheries Service (NMFS) federal management areas in blue (WGOA, CGOA and EGOA representing the western, central and eastern GOA, respectively). The deployed and pop-up end locations for each skate are denoted in black triangles and red circles, respectively. The lines connecting deployed and end locations are the hypothetical minimum distances traveled by the skate. A. Location of the GOA in the North Pacific is shown, with the extent of the study area designated by the red dashed box. B. Prince William Sound (PWS) is shown in greater detail.

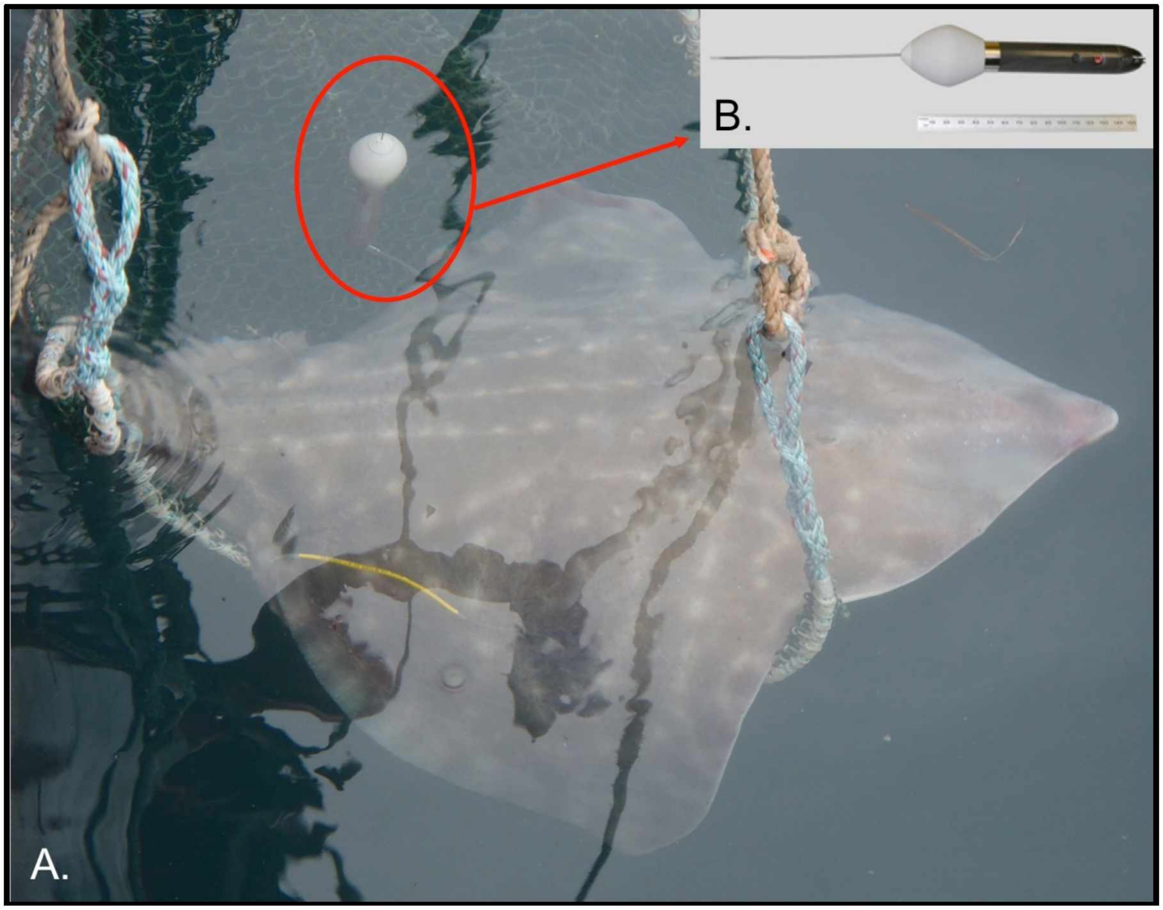
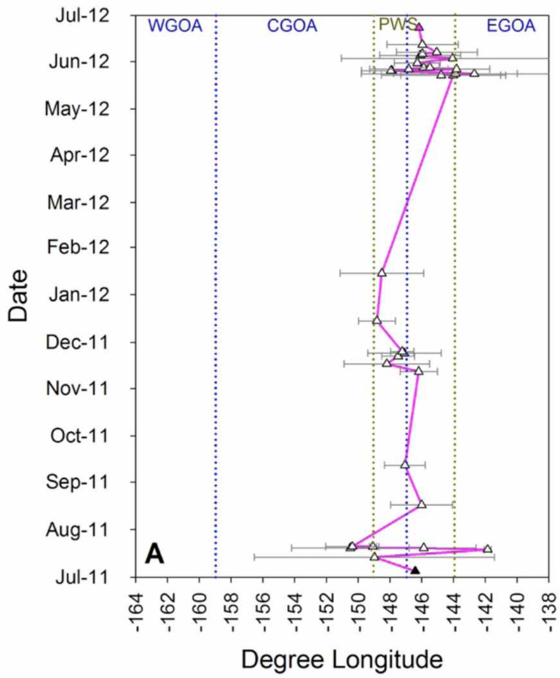


Figure 1.2. Photograph of tagged big skate F145 being released with a PSAT tag attached. A. The skate is being lowered in the water in a net. B. A close-up of the PSAT tag



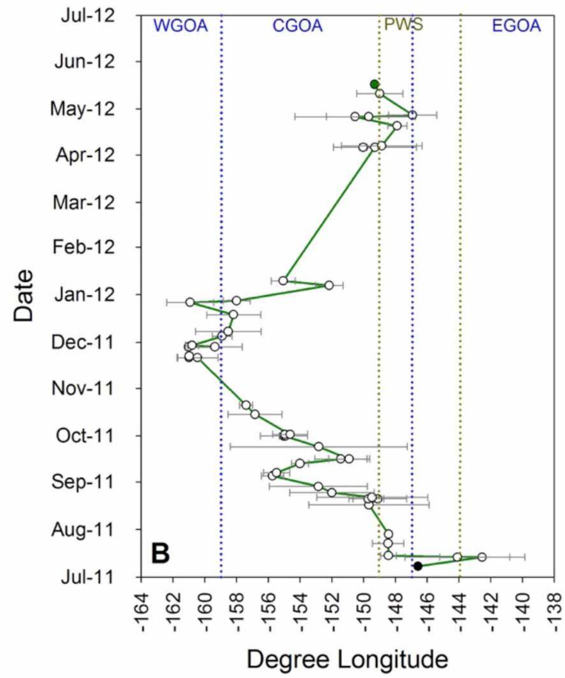


Figure 1.3. Example longitudinal tracks of two dispersal types. The longitude tracks of tagged big skates F145 (A, pink line) and M124 (B, green line) while at liberty are shown. The initial black symbols represent the known tagging locations, and the final colored symbols represent the Argos position of the first location upon pop-up. Open symbols are the estimated longitudes produced by Wildlife Computers software, with the uncertainty of each location represented by the grey horizontal error bars. Dotted vertical lines represent the longitudinal boundaries of the U.S. federal (blue) and State of Alaska (yellow) management areas. WGOA = western Gulf of Alaska, CGOA = central GOA, PWS = Prince William Sound, EGOA = eastern GOA.

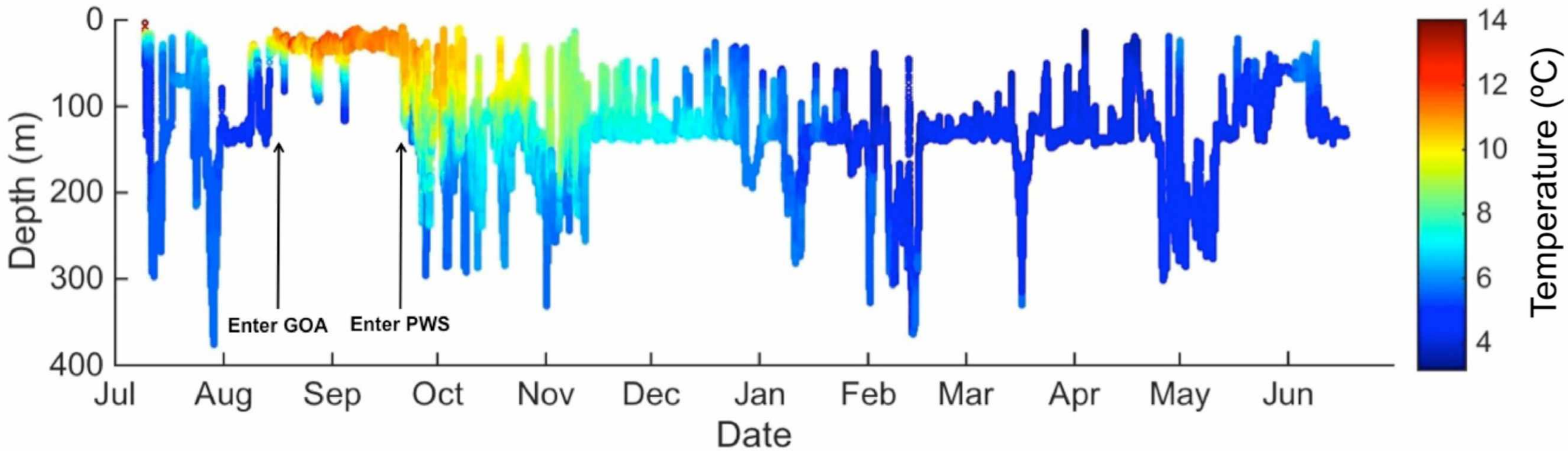


Figure 1.4. Depth and temperature profile of the skate for which the tag was recovered (F164) while at liberty in 2011 and 2012. The line represents depth of the skate over time, and the color of the line represents the temperature experienced by the skate. Black arrows show the possible times of movement from Prince William Sound (PWS) to the Gulf of Alaska (GOA) in mid-August, and from GOA back into PWS in mid-September.

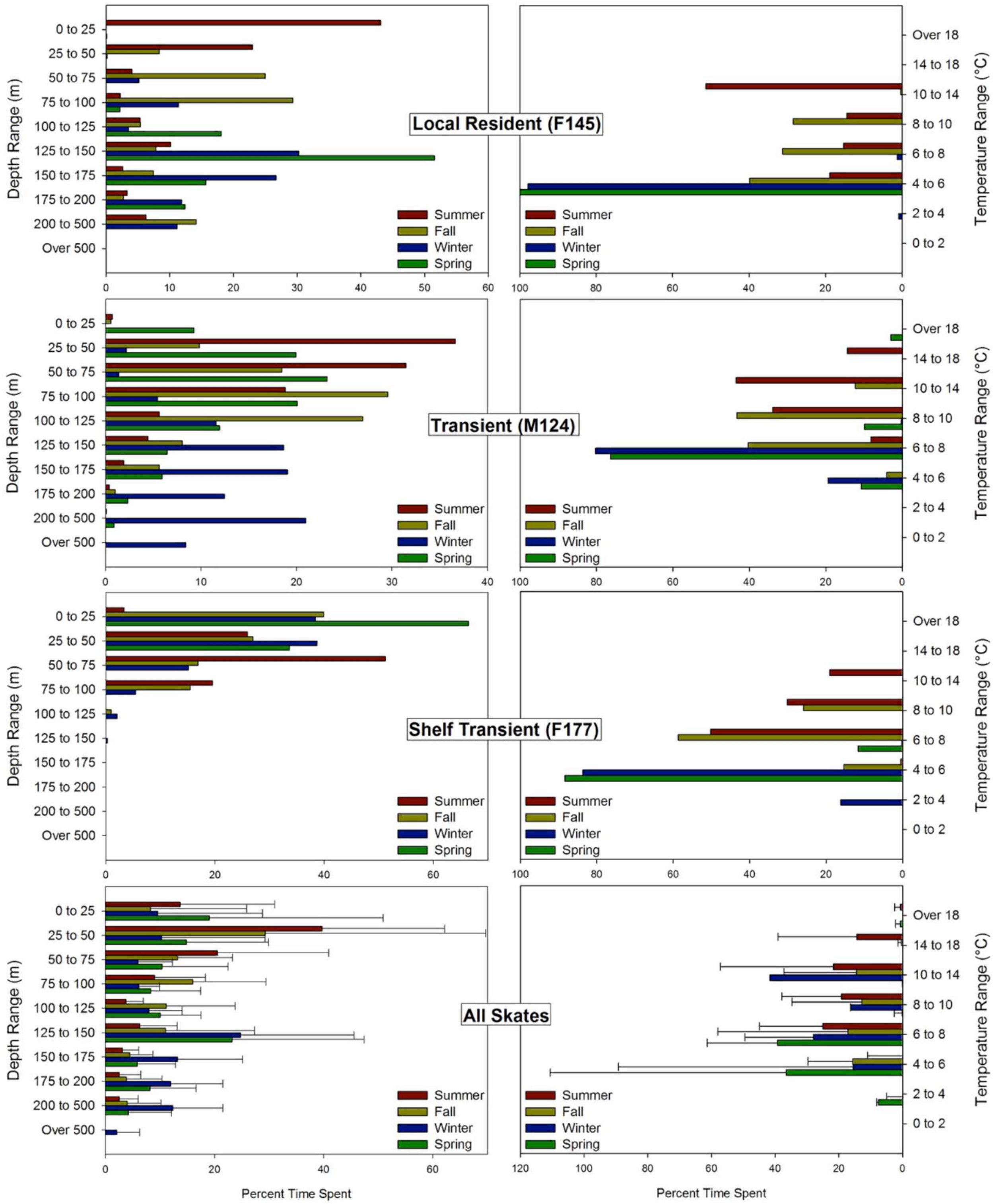


Figure 1.5. Percent time spent at different depth and temperature ranges. Depth (left column) and temperature (right column) use are shown for the three behavior types (using an example skate identified by sex and TL), plus all skates, during each of the four seasons. Error bars for all skates are 1 SD.

Chapter 2: First Stock Assessment Models for Big (*Beringraja binoculata*) and Longnose (*Raja rhina*) Skates in the Gulf of Alaska: Development of a Stock Synthesis Model[3]

2.1 Abstract

Big (*Beringraja binoculata*) and longnose skate (*Raja rhina*) are abundant and frequently caught by fishermen using longline and trawl gear in the Gulf of Alaska. However, their low reproductive output and longevity render them vulnerable to overfishing. Consequently, only non-target catches are permitted to be landed. Skates command relatively high ex-vessel prices (up to US$1/kg) owing to worldwide demand, prompting interest by the fishing industry in Alaska to be allowed to take larger skate harvests. However, fishery managers are unlikely to allow higher catches until it can be demonstrated that skate stocks are capable of sustaining increased harvest rates. Recently, the increased availability of information on life history, population structure, fecundity, and movement has facilitated development of complete quantitative stock assessments for some species within the skate complex. We developed a stock assessment for big and longnose skates in Alaska, using Stock Synthesis, a powerful software package that is sufficiently flexible to handle data-limited situations. Single-sex models include longline and trawl fishery data, and incorporate two fishery independent surveys. Models show declines in both big and longnose skate stocks in the Gulf of Alaska since 2004; however neither stock has been reduced to B_{MSY}, the biomass that produces the maximum sustainable yield (MSY). We estimated MSY to be 4,570 mt for big skates and 3,812 mt for longnose skates. As these

[3] Farrugia, T. J., Kruse, G. H., Taylor, I. G., Ormseth, O. A., and Seitz, A.C. *In prep.* First stock assessment models for big (*Beringraja binoculata*) and longnose (*Raja rhina*) skates in the Gulf of Alaska: Development of a Stock Synthesis model. Fisheries Research.

MSY estimates are slightly larger than the current catch quotas and MSY forms the basis for defining overfishing limits, there appears to be little scope for substantial increases in skate landings in the Gulf of Alaska without jeopardizing the sustainability of the stock. These inaugural stock assessment models provide state and federal fishery management agencies with quantitative tools to formulate conservation and management measures that prevent overfishing, while achieving optimum yield on a long-term, sustainable basis.

2.2 Introduction

Fish stock assessments are central to responsible management of fisheries worldwide (Hilborn 2012; NMFS 2001), providing fishery managers with estimates of the past and present status of fish stocks, as well as future predictions (Worm et al. 2009). Quantitative stock assessments can also reduce uncertainty in fishery management decisions and help to define important fisheries management targets, such as biological reference points (Caddy and Mahon 1995). Today, a substantial number of software packages are available to produce stock assessment models (for a review see Dichmont et al. 2016); and, while these vary in the quantity and resolution of data that they require, all depend on a minimally sufficient amount of information, which can restrict their application to data-limited species.

Elasmobranchs (sharks, skates, and rays) are frequently data-limited and poorly studied (Jiao et al. 2011). Data on total catches, bycatch, and discard mortality are frequently poor, and catch records are often inaccurate because of misidentification or lumping of species groups (Clarke et al. 2006). Moreover, other complications of managing elasmobranch fisheries include their large size, late maturation, and low number of offspring, which can quickly lead to overfishing (Dulvy et al. 2014) and long rebuilding times for depleted stocks (Dulvy and Reynolds 2002). Therefore, it is crucial to develop stock assessments for elasmobranch species as soon as sufficient information is available and before a stock becomes depleted.

Skates (Rajiformes: Rajoidei) are dorso-ventrally compressed elasmobranchs that frequently inhabit deep and/or high latitude areas of the oceans (Last et al. 2016). They are caught globally in either directed or non-target fisheries mainly for their pectoral fins or "wings", largely for European and Asian markets (ADCCED 2009). In 2012, 28,000 metric tons (mt) of skates worth over US$17 million were caught in the United States (NMFS 2013). Overall, the U.S. is a net exporter of skates, most of which come from the Atlantic Ocean. However, some of the Atlantic skate stocks have been subject to fishery-induced population declines, mainly as a result of discard mortality in non-target fisheries. For example, the thorny skate (*Amblyraja radiata)* has recently been listed as a species of concern as a result of overfishing in the U.S. federal directed skate fishery (NOAA 2016). Although the skate species under directed harvests in this fishery are well-managed, retention of thorny as well as smooth skates (*Malacoraja senta*) is still currently prohibited (Curtis and Sosebee 2015), and barndoor skates (*Dipturus laevis*) were only recently declared rebuilt after being managed under a 13-year rebuilding plan (NEFMC 2016). In Europe, the common skate (*Dipturus batis*) has been extirpated from the North Sea due to fishing (Walker and Hislop 1998).

In contrast, in the North Pacific Ocean, and in waters around Alaska in particular, skates are not considered to be overfished or threatened by overfishing at present (Orsmeth, 2016a,b; NMFS 2013). Many fishers actively avoid skates when targeting other benthic species, and it has been suggested that landings could be increased without undue risk of stock collapse. Consequently, the fishing community in Alaska has expressed interest in management measures that would increase fishing opportunities for skates in the Gulf of Alaska (GOA). Accordingly, the Alaska Department of Commerce, Community and Economic Development encouraged the development of skate fisheries in Alaska (ADCCED 2009).

Of the 15 species of skates found in Alaskan waters, big skates (*Beringraja binoculata*) and longnose skates (*Raja rhina*) are the largest (Eschmeyer et al. 1983) and most commonly captured in the GOA, and represent 68% of the estimated skate catch there since 2005 (Ormseth 2015). Prior to 2003, there were no directed fisheries for skates in Alaska, and all skate species were managed within an aggregate "Other Species" category that also included miscellaneous species of sculpin, shark, squid, and octopus (Ormseth 2013; Ormseth and Matta 2009). In 2003, a directed fishery developed for big and longnose skates in federal waters in the GOA, which led to these species being removed from "Other Species" and managed as individual stocks beginning in 2005. At that time, the directed fishery was closed due to lack of data regarding stock status and high levels of incidental catch (Ormseth 2015). In 2009 and 2010, a skate fishery was permitted in GOA state waters, but was discontinued because funds were insufficient to collect adequate biological data for management. Both of these directed fisheries were motivated by a desire by industry to diversify catches and the relatively high ex-vessel price (US$280 – 950/mt between 1995 and 2015) for skates, similar to or higher than the price paid for Pacific cod, *Gadus macrocephalus* (Alaska Department of Fish and Game Commercial Operator's Annual Report, accessed in January 2017).

Although skates are not currently targeted in U.S. federal or Alaska state waters of the GOA, big skates and longnose skates are commonly retained in flatfish trawl fisheries and in longline fisheries for Pacific cod and Pacific halibut (*Hippoglossus stenolepis*; Stevenson and Lewis 2010). Skate retention rates were highest in 2003 (90%) when the first directed fishery opened. Since then, at least 50 – 60% of the big skates and longnose skates caught in the GOA (Stevenson and Lewis 2010), averaging 3,265 mt per year for both species combined, have been retained (Ormseth 2015). Actual skate catch is likely to be higher than reported because of bycatch in unobserved fisheries, such as the Pacific halibut Individual Fishing Quota (IFQ) fishery (Ormseth 2013). The North Pacific Fishery Management Council (NPFMC) currently manages big and longnose skates as Tier 5 species, meaning that the stocks are managed with little biological data and conservative harvest levels are set using estimates of biomass and natural mortality only. For Tier 5, instantaneous rates of overfishing are equated to assumed natural mortality rates (M) and rates of fishing corresponding to acceptable biological catch (ABC) are constrained at $\leq$0.75 M. Additional information, including biological reference points estimated from stock assessment models, is needed to advance skate management to a higher-level tier, which would reduce the perception of risk and increase our confidence in the estimation of stock size. Stock assessment models do not exist for either skate species and further development of skate fisheries in Alaska requires a better understanding of big and longnose skate population dynamics.

Fortunately, over the last ten years, additional biological information on skates has been accumulated by fisheries scientists, enough to now support development of quantitative stock assessment models for big skates and longnose skates. Specifically, new information on skate catches, diet (Bizzarro et al. 2007; Ormseth 2011), age and growth (Gburski et al. 2007; McFarlane and King 2006), reproductive biology and maturity (Ebert et al. 2008), distribution (Bizzarro et al. 2014; Stevenson et al. 2008), and movement (Farrugia et al. 2016) are now available. In this paper, we develop population dynamic models for skates in the GOA, and use the models to estimate biological reference points. We further use the models to conduct sensitivity analyses. By examining a range of initial values for the parameters, we are able to determine which assumptions most strongly influence model outcomes. Resolving the values of those parameters is high priority for future work, and we recommend research priorities based on the importance of assumptions to model results. Our goal is to provide a case study that shows the utility of developing stock assessments for all species for which there are sufficient available data.

2.3 Methods

2.3.1 Software

We used Stock Synthesis 3 (SS3), a general stock assessment computer program (Methot and Wetzel 2013; Punt and Maunder 2013), to model big skate and longnose skate stocks in the GOA. SS3 uses an implementation of Integrated Analysis (Maunder and Punt 2013) and is coded with Auto-Differentiation Model Builder. As such, it is a powerful tool, capable of efficiently estimating hundreds of parameters using maximum likelihood methods. In addition, SS3 is flexible regarding the types of data it can integrate, and scalable to the amount of data available. Thus, it is a valuable stock assessment tool for species like skates that are data-limited, and for which future improvements will be made as additional fisheries-dependent and fisheries-independent data become available.

Outputs from SS3 models were examined using R (R Core Team 2014). Specifically, we used the R4SS package (Taylor et al. 2015), which is a collection of R functions to summarize, manipulate and visualize results from SS model runs. We also used R to create plots and estimate summary statistics.

2.3.2 Data sources

Several data types were extracted from primary literature and government reports. Biological information for the model was obtained from the primary literature, including estimates of growth and longevity (Gburski et al. 2007) and maturity (Ebert et al. 2008). One year (2009) of size-at-age data was acquired from the Alaska Fisheries Science Center (AFSC) of the National Marine Fisheries Service (NMFS); age estimates were produced by counting vertebral annuli of both species (King et al. 2015). Each age was determined by two readers, allowing us to estimate ageing errors, using the methodology and R code from Punt et al. (2008).

Catches and length compositions of skates captured incidentally in the GOA were obtained from the NMFS Alaska Regional Office catch accounting system. Skate catches were aggregated into two “fleets” based on gear type, irrespective of the target fishery in which skates were captured. The “longline” fleet included all catches from longline and jig fishing vessels, and the “trawl” fleet included combined catches from the trawl and pot fishery vessels. Before 2004, fishery catches were not recorded to the species level. To fill this gap, we multiplied the average species composition by gear type during 2004 – 2013 by the total estimated catches of each gear type from 1992 to 2003. Thus time series of catch and apportioned-catch for big skates, longnose skates, and “other” skates available for modeling extended from 1992 through 2013 (Figure 2.1). Length compositions of skates captured in both fleets were only available starting in 2009; earlier sample sizes were too small to be reliable. Because fishing did not occur equally in all years and statistical areas, we weighted length frequencies based on the total catch in each year/area.

Fisheries-independent data used in the model included observations from the NMFS trawl and the International Pacific Halibut Commission (IPHC) longline surveys. The NMFS GOA trawl survey started in 1984 as a triennial survey and became biennial in 1999. This survey employs chartered commercial trawlers using a standardized four-seam bottom trawl with 24.2 m-wide roller gear (for full description of the survey, see Raring et al. 2016). The trawl survey covers depths from 10 to 1,000 m and follows a stratified random sampling design based on depth, terrain and statistical area. The trawl survey biomass estimate was then calculated using an area-swept method (Raring et al. 2016).

A longline survey has been conducted by IPHC annually since 1998 (Henry et al. 2014). Survey stations extensively cover coastal areas of the GOA from 36 to 500 m depth. Although the survey targets Pacific halibut, the first 20 hooks of each 100-hook section of longline are examined for other species (Henry et al. 2014). Numbers of big skates and longnose skates recorded in this survey were converted to indices of abundance using a general linear model with a binomial error structure to account for presence or absence on each hook (Gertseva and Taylor 2012).

Length composition data from all fleets were transformed to proportions of abundance in 4-cm length bins. Length compositions for the trawl survey were available starting in 1996, but for the longline survey they were only available for 2013 during a *Raja* sampling pilot study, as lengths of skates were not recorded consistently in other years (Kohler

2014). Other sources of fisheries-independent data were considered, including the NMFS annual longline survey and the Alaska Department of Fish and Game (ADFG) large mesh trawl survey. However, these were not used because they either did not capture skates consistently, or had a very restricted geographical range.

2.3.3 Model structure and parameterization

The stock assessment model was built as an age-structured population dynamics model and includes data from 1984 to 2013. Although there is some information from 2014 and 2015, the structure of the fisheries observer program in the North Pacific changed after 2013, which may have affected catch and discard estimates. Until a longer post-2013 time series is available, we truncated the data at 2013 to improve consistency. The model was used to forecast the estimated parameters until 2023.

We made several simplifying assumptions to leverage the limited data. We assumed one 12-month long fishing season per year, with no differences in parameters between sexes for either species, reducing the number of parameters that needed to be estimated. We also assumed that there were no environmental variables affecting the stocks, and no morphological differences across the geographic range of each skate species. Based on tagging data for big skates (Farrugia et al. 2016; King and McFarlane 2010), we assumed one GOA-wide stock for both big skates and longnose skates (i.e., fully mixed populations of each species throughout the entire GOA).

The individual growth of both species was modeled as a von Bertalanffy curve, with starting parameter values based on values reported in the literature (Ebert et al. 2008; Gburski et al. 2007). Variability in length at each age was assumed to be normally distributed, with a coefficient of variation of 0.1. The stock-recruitment relationship was modeled using a standard Beverton-Holt curve, although no species-specific values were available to use as inputs. We therefore allowed the model to estimate the virgin recruitment level and steepness of the stock-recruitment curve. The approximate true average recruitment deviation of the spawner-recruitment curve, designated as σ_R, was fixed in the model at 0.3. This value was chosen to balance the biology of skates, which have low fecundity and likely experience low recruitment variability, and the uncertainty of the spawner-recruitment relationship, for which we have very little information. Instantaneous natural mortality was initially set at 0.1, which is assumed in the current stock assessment for GOA skates (Ormseth 2015), but was allowed to be estimated within the model.

Selectivity and catchability of the two fleets and two surveys were parameterized within the model with no *a priori* information, because no species-specific data exist. Size selectivity, the efficiency of the fishing gear to capture individuals of different sizes, was initially modeled as a logistic curve for all four fleets (two fisheries and two surveys). The reasoning behind the asymptotic assumption is that, for both trawl and longline gear, smaller skates should be less likely to be captured (e.g., they can escape through the trawl mesh, and the longline hook is too large), and capture probability should increase with size. However, catchability, the average portion of a stock that is taken by each unit of fishing effort, is a much more difficult parameter to assess based on first principles. As such, we used catchability of the trawl survey as a scaling factor to the biomass available to the fishery, and initially set this scaling factor at 1 to mirror what is currently used in the Alaska skate (*Bathyraja parmifera*) assessment (Ormseth 2016). Catchabilities of the longline survey and the fishing fleets were then estimated analytically within the model as the median unbiased estimate (Ludwig and Walters 1981).

The parameterization of the model described above was used to form the preferred model. The choice of this configuration as the preferred model was based on its parsimoniousness, the model converging properly on all parameters that yielded reasonable biomass estimates that were consistent with survey and fishery catch rates, and age composition estimates that adequately mirrored the age composition from all four fleets. For a full list of model parameters, see Appendix A.

2.3.4 Sensitivity analyses

From this preferred model, we ran a series of alternative models, each one representing a change in only one parameter. These sensitivity analyses allowed us to examine how the model responded to different assumptions and parameter choices (Majkowski 1982). Four different modifications were made to the preferred model: 1) modification of the selectivity pattern for all four fleets, 2) alternative values for σ_R, 3) likelihood profile over the catchability index (i.e., scaling factor), and 4) alternative catch histories in which we assume under-reporting of skate discards.

For selectivity, the preferred model assumed an asymptotic curve for each of the two fleets and two surveys in the model. However, it is possible that selectivity is highest at intermediate skate sizes, with the largest skates being able to either avoid or escape the trawl gear or remove the bait from a longline without being hooked. In addition, the shape of the chosen selectivity curve can bias the results of the stock assessment (Wang et al. 2014), and this may not be immediately apparent in situations with multiple fleets that may all have different underlying selectivity curves (Sampson and Scott 2012). For these reasons, we examined the sensitivity of the model to the shape of the selectivity curve by considering an alternative four parameter double normal model with dome-shaped selectivities for all four fleets.

The initial value chosen for σ_R was 0.3; but, because of uncertainty in the spawner-recruitment relationship, we decided to analyze the outcomes of the stock assessment model under two other scenarios: one in which there was no deviation in recruitment (σ_R=0) and one with twice the assumed amount of variation (σ_R=0.6).

Catchability, or the overall gear efficiency of a fishery, is another parameter that is difficult to estimate (Hilborn and Walters 1992) because it integrates many factors such as population biology, gear type, fishing pressure, harvest strategy and environmental fluctuations (Arreguín-Sánchez 1996). In light of the limited data on skates in the GOA, we set trawl survey catchability to unity for our preferred model. This assumes that there were no biases in catch estimates due to some portion of each stock being more or less available to the fishing gear. To test this assumption, we ran a likelihood profile on the catchability parameter, allowing it to vary approximately from 0.05 to 20. This may be an unrealistically large range of catchability values, but one that would clearly show the impact of this parameter on the model. Values above 1 represent a positive bias in the available biomass, such as a herding effect of the trawl, or areas that were not sampled having lower skate densities. In contrast, values below 1 represent a negative bias, which might result from skates avoiding capture or occurring at higher densities in areas inaccessible by the fishing gear.

Finally, we examined the effect of potentially unreported catch in the early years of skate retention. Although good estimates of skate retention are available after 2003 (Stevenson and Lewis 2010), skate species identification and retention are less well understood before 2003, likely leading to an underestimation of the total catch of skates. Therefore, to test the sensitivity of the stock assessment model to the unreported or under-reported discards, we inflated the catches of big skates and longnose skates by 200, 500, 1,000 and 1,500 mt per year for the years 1992 – 2002, mimicking situations in which discards were unreported in the early years before landings increased.

2.4 Results and Discussion

2.4.1 Preferred model outputs

Models for both big skates and longnose skates were successfully fit to the same types and amounts of data (Figure 2.1), demonstrating that SS models could be fitted to provide stock assessment information even in relatively understudied and data-limited species. Model results for big skates and longnose skates underscore the difference in population dynamics and biomass of these two species in the GOA (Table 2.1). Overall, the annual total biomass estimated by the preferred model for big skates was fairly constant until 1998, after which a slow decline began (Figure 2.2). Longnose skates are estimated to have experienced a modest increase in biomass starting in 1990, followed by an equally modest decrease starting in 2003. The biomass of both species is now estimated to be lower than their virgin stock levels, almost certainly due to the increase in fishing pressure beginning in 2003. The unfished biomass of longnose skates was estimated by the model as being almost twice that of big skates, with both populations having been drawn down by about

10,000 mt since the beginning of the time series through 2013 (Table 2.1). Further model outputs for the two preferred models can be found in Appendix A.

The estimated maximum sustainable yield (MSY) was larger for big skates (4,570 mt) than longnose skates (3,812 mt). Both of these values are smaller than the currently specified overfishing levels of 5,086 mt and 4,274 mt, respectively (Ormseth 2016). Current ABC levels are set at 3,814 mt for big skates and 3,206 mt for longnose skates (Ormseth, 2016). Given our first quantitative stock assessment models of big and longnose skates, which we consider provisional, we do not advocate policy recommendations at this point. However, we suggest these results provide some evidence that current catch rates appear to be sustainable, but that an increase of more than 20% in catch of either species would likely lead to threats to these skate populations. Because the fishing industry has been harvesting big skates at higher rates than longnose skates, it is no surprise that the biomass ratio (B_{ratio}), calculated as the current biomass divided by the biomass at MSY (B_{MSY}), is very close to 1 for big skates, but over twice that for longnose skates.

The life history parameters on which the preferred models converged are consistent with the existing literature. Natural mortality was similar (~0.25) for both big skates and longnose skates in this study (Table 2.1). For big skates, this is very similar to the estimate of 0.28 obtained by Gburski et al. (2007) for skates in the GOA, through an approach based on maximum age (Hoenig 1983). Gburski et al. (2007) estimated longnose skate natural mortality at 0.17, substantially lower than our estimate; but longnose skates off the US West Coast were found to have a natural mortality of 0.26, virtually identical to our estimate (Thompson 2006).

Maximum length (L_∞) was estimated to be higher for big skates (185.1 cm total length TL) than for longnose skates (162.1 cm TL), consistent with previous studies. For big skates, this is very close to the initial input into the model of 189.6 cm TL taken from Gburski et al. (2007), and substantially smaller than the estimate of 213.9 cm TL from British Columbia (McFarlane and King 2006). This suggests either a geographic segregation of the population based on size, or provides evidence of separate populations in the GOA and British Columbia, with different life history parameters. However, tagging studies indicate that big skates are capable of long distance movements over 2,000 km (Farrugia et al. 2016; King and McFarlane 2010), which is inconsistent with the latter explanation. Longnose skates show variation in maximum length estimates in previous studies, from 96.7 cm TL in California (Zeiner and Wolf 1993) to 234.1 cm TL in the GOA (Gburski et al. 2007). Our estimate of 162 cm TL is consistent with the majority of the fishery and survey catch compositions, although a few individuals caught in the longline fishery reached up to 196 cm (Ormseth 2015). It is possible that these were instances in which big skates were misidentified as longnose skates. Longer time series of both the survey and fishery catch composition, as well as increased familiarity with the species, will hopefully ameliorate this discrepancy in the future.

The estimated von Bertalanffy growth rate (K parameter) was larger for big skates than longnose skates (Table 2.1). This finding is consistent with the fact that big skates grow larger and attain a younger maximum age than longnose skates (Gburski et al. 2007). The growth rates of big skates in the GOA were found to vary between 0.08 for males and 0.15 for females, with the combined estimate regardless of sex at 0.12 (Gburski et al. 2007), very similar to our estimate of 0.13. Longnose skates also had similar estimates of growth rates in our model (0.07) compared to those found by Gburski et al. (2007) of 0.04 for females and males combined. Growth rates estimated for British Columbia were similar to those in this study for longnose skates, but were much smaller (0.05 compared to our 0.13) for big skates, consistent with their estimate that big skates grow much larger in British Columbia, up to 293 cm TL (McFarlane and King 2006).

2.4.2 Sensitivity analyses

2.4.2.1 Dome shaped selectivity curves

For big skates, the dome shaped selectivity curve with eight extra parameters increased the likelihood of the total model, as well as for each of the following model components: survey index, length composition and size-at-age data (Table 2.2). All of the other reference points were relatively similar to the preferred model, and as expected, the total biomass time series showed the same trend, but with an overall increase in biomass (Figure 2.2). However, the dome shape selectivity curve produced a less reasonable estimate for maximum length for big skates of 300 cm TL. Although this is only slightly above the estimated maximum length for big skates in British Columbia (McFarlane and King 2006), it is much larger than estimates for the GOA (Gburski et al. 2007) and much larger than the largest recorded big skate caught in the GOA at 192 cm TL (AFSC, unpublished data). Congruously, the growth rate estimated by this alternative model was about half that of the preferred model, and the resulting virgin spawning biomass was larger (Table 2.2). Given these less reasonable estimates, and because the change in total likelihood was minimal, the more parsimonious asymptotic selectivity model was retained as the preferred model.

For longnose skates, the likelihood of the dome shaped selectivity model was also very similar to the asymptotic selectivity model overall (Table 2.2). The largest differences came from the estimates of natural mortality and MSY, which were both drastically lower in the dome shaped selectivity model (Table 2.2). The yield at MSY is particularly salient to management, as it was less than half of the yield estimated by the preferred model. As in the big skate model above, the virgin spawning biomass of longnose skates was much larger under a dome shaped selectivity assumption. The time series of total biomass showed that inclusion of the dome shape model led to an increase in biomass estimates and also flattened the population trend curve suggesting that fishing has had little effect on the population.

As with longnose skates, although the dome shape curve resulted in a slightly better total likelihood for the big skate model thanks to the addition of eight parameters, we elected to use an asymptotic selectivity curve for future models on the grounds that it was more parsimonious and provided more plausible parameter estimates. Size selectivity of fishing gear was directly evaluated for skates in Alaska by only one study, which found that a monotonically increasing logistic selectivity curve had the best fit (Kotwicki and Weinberg 2005). That study, however, was conducted in the Bering Sea on a complex of five skate species of the genus *Bathyraja*, which grow to substantially smaller sizes than big or longnose skates. The asymptotic and dome shaped curves fit the data in that study nearly as well as the logistic curve. Therefore, we find the asymptotic selectivity curve to be the best choice at this time and suggest it be used in future stock assessment models for big and longnose skates in the GOA. Certainly, this is an area for future research.

2.4.2.2 Alternate recruitment deviations

Due to the lack of information on the reproductive frequency, fecundity and developmental times of embryos in big skates and longnose skates, we initially fixed the recruitment deviation parameter, σ_R, at 0.3. The number of age-0 recruits under this scenario mostly varied between 2,500,000 and 4,200,000 for big skates, with a single-year peak in 2011 at 5,911,000 (Figure 2.3A). Longnose skate recruitment mostly varied between 15,000,000 and 32,000,000 recruits with a single-year peak in 1988 of 62,473,000 (Figure 2.3B). When recruitment deviation was set at 0, age-0 recruits were constant at 2,800,000 for big skates and 23,250,000 for longnose skates throughout the study period. By contrast, when deviations were doubled to σ_R =0.6, recruit numbers were naturally more variable, but this variability was manifested differently for each species (Figure 2.3). In big skates, increasing deviations also increased the estimated number of recruits in most years, whereas in longnose skates, this generally decreased the number of recruits. The years of peak recruitment in both species, however, had much higher recruitment when σ_R =0.6. The total biomass estimates were not substantially altered when recruitment deviations were modified for big skates (Figure 2.2A), and they were slightly reduced in longnose skates when recruitment deviations were increased (Figure 2.2B).

The likelihood of the no recruitment deviation model (σ_R =0) was higher than the preferred model for big skates; but for longnose skates, the high deviation model had a higher likelihood (Table 2.2). However, these alternative recruitment deviations did not substantially change any of the life history parameter estimates. For longnose skates under the σ_R =0 model, the biomass ratio in 2015 was drastically lower and the yield at MSY was substantially higher. These results seem contradictory and an indication that the model did not converge well under these conditions. As a result, we deemed the intermediate value of 0.3 to be most appropriate for both big and longnose skates.

2.4.2.3 Catchability likelihood profile

The catchability parameter was the most influential parameter on model outputs. A likelihood profile across catchability estimates showed that in both big skates and longnose skates, there was a drastic increase in the negative log likelihood for catchabilities larger than 1.65 (Figure 2.4). The likelihood of the catchability in the preferred model was within 10% of the highest total likelihood value for a catchability value of 0.05. In both species, the likelihoods of the four data components also show similar trends, with length and survey index data increasing in negative log likelihood, particularly with a catchability of 1.65, and the size-at-age data showed a moderate decrease in negative log likelihood over the range of catchabilities (Figure 2.4). At a high catchability (> 7.39), not only is the likelihood of the model much lower, nearly all of the life history parameters and reference points also differ substantially from the preferred model (Table 2.2). In particular, the natural mortality and maximum length estimates are drastically increased, and most of the biomass reference points are much lower. At low catchability values (< 0.14), the likelihood is slightly improved and all the life history parameters are relatively unchanged, but the biomass reference points are much higher (Table 2.2). This is consistent with the fact that, if the model assumes that the trawl survey is only catching a small percentage of the available biomass, it will estimate higher total biomass.

The difficulty arises when management needs to decide on which catchability value to use and therefore which biomass level is most reasonable. Estimates of catchability for skates are not readily available in the literature. For example, the catchability of skates in trawls in Canadian Atlantic waters is higher at night than during the day and increases with depth (Casey and Myers 1998), but this is still only a relative measure of catchability. Moreover, those results cannot be extrapolated to big skates and longnose skates in the GOA, as that study employed different trawl gear than used in the GOA. Given the dearth of available data, and until more reliable estimates of catchability can be obtained, we suggest using the more conservative end of the catchability range while still retaining a high model likelihood, such as the catchability value of 1 used in the preferred model. This is also the catchability currently used in stock assessment models for Alaska skates in the BSAI.

2.4.2.4 Alternate discard history

The models for both big and longnose skates were stable when increases in discard rates were simulated pre-2003 (Table 2.2). Increasing discards by 200, 500, 1,000 or 1,500 mt per year before 2003 did influence the life history parameters. Even adding 1000 mt per year in unaccounted discards only moderately affected the biomass reference points, slightly increasing the virgin spawning biomass, unfished biomass and yield at MSY for both species (Table 2.2). However, in the most extreme case for longnose skates, adding 1,500 mt to the discards substantially lowered the biomass ratio from 2.30 in the preferred model to 0.24 in the discard-added model, and drastically increased the yield at MSY to over 13,000 mt. These differences could have far-reaching implications for management as it could provide a very different understanding of the current status of the stock and thus the ABC that management would set.

Although we have evidence that the retention of skates has increased since 2003 (Stevenson and Lewis 2010), unaccounted discards were likely much higher in the past. In the present study, the model seems to be stable to assumptions of all but the most extreme scenarios of unreported discards. As more studies on the amount of skate discard mortality are conducted, these data should be integrated into the SS model to better account for this source of mortality. Although discard mortality is currently considered to be 100% for big and longnose skates in the GOA, studies for other skate species suggest that mortality rates can be as low as 19% (Mandelman et al. 2013). However, there is substantial variation in discard mortality rates between species and locations, so studies specifically on big and longnose skates with commercial fishing gear typical of the GOA are needed.

2.5 Conclusion

This study demonstrated the feasibility of producing stock assessment models for two skate species in the GOA, even under current data limitations, and that these models are informative for management purposes. Our expectation is that this model will be used as a foundational framework to which updated information and new data sources can be added to further refine future stock assessments for skates. We recommend that during each update of the stock assessment, the preferred model be compared at a minimum to models with 1) dome-shaped selectivity curves, 2) lower catchability estimates, and 3) alternate recruitment parameter estimates, owing to the effects of these parameters on model results. These alternative models can be used to test the assumptions on which the preferred models are based, providing additional insight into the uncertainty surrounding the assessment of stock status and reference points. Development of such alternative models can also form the basis for management strategy evaluations to examine harvest strategies that are robust to these uncertainties.

Although it would be premature to offer management recommendations for the big and longnose skate stocks in the GOA at this time, we can provide insight into possible reference points. Virgin total biomass estimates for big skates (58,000 mt) and longnose skates (106,000 mt) supply the scale of the unfished populations, and can be compared to the current trawl survey-based biomass estimates of 50,857 mt for big skates and 42,737 mt for longnose skates. While the biomass estimates for big skates were very similar between our model and the trawl survey, for longnose skates there was a large discrepancy. Because our model included the trawl survey as an input in addition to observations from the IPHC longline survey and the catch history, we suggest that the diversity of fishery-dependent and fishery-independent data sources in our model provided a better assessment of the longnose biomass than does one trawl survey alone. In addition, the trawl survey is conducted primarily in waters shallower than 200 m, corresponding to the optimal depth range of big skates; but longnose skates frequently inhabit depths to 1,000 m (Eschmeyer et al. 1983), and the trawl survey may be missing a substantial portion of the longnose population. Our results are also consistent with the fact that similar numbers of big skates and longnose skates have been taken in the fishery, but big skates have almost double the growth rate of longnose skates. This would only be possible if the population of longnose skates was larger than that of big skates.

Of particular interest to management, the current biomass ratio for big skates is repeatedly estimated around 1, suggesting that big skate biomass is close to B_{MSY}. For longnose skates, our models suggested that their biomass remains up to twice B_{MSY}. The

MSY for big skates is > 4,000 mt in most model alternatives, and 4,570 mt for the preferred model (compared to average catches of 2,300 mt during 2009 – 2013); and the yield at MSY for longnose skates is 3,812 mt in the preferred model (compared to average catches of 1,395 mt during 2009 – 2013). As a comparison to the current Tier 5 management, if these yields at MSY are set as the overfishing levels (OFL) and a precautionary approach is taken which sets the ABC equal to 0.75 times the OFL, it would lead to an ABC of 3,427 mt and 2,859 mt for big and longnose skates, respectively. For both species, this would represent a slight decrease in the current ABC, set at 3,814 mt for big skates and 3,206 mt for longnose skates, but still be higher than the catches in any year since 2005 (Ormseth 2015). Additionally, this added information may allow management to use a less conservative precautionary factor than 0.75, such as the Tier 3 approach currently used for Alaska skate in the Bering Sea (Ormseth 2016). However, care should be taken in applying the estimates from this study, especially with longnose skates whose MSY varied substantially depending on the parameterization of the model. This variation points to the need to collect additional information to further improve the model. It is also important to remember that these reference points are based on estimates of abundance that are subject to error, and should therefore be applied with caution (Hilborn 2002).

Many simplifying assumptions had to be made in these stock assessment models due to a dearth of information. This is unlikely to change in the near future, so researchers and managers should always keep a precautionary approach and acknowledge the inherent uncertainty in the data, and integrate the range of outputs from various model alternatives. Meanwhile, research efforts should be expanded to address the most urgent data needs. Specifically, we suggest focusing research on estimating catchability for big skates and longnose skates, and determining the most appropriate size selectivity curve for trawl and longline gears. Another research priority should be a better understanding of the reproductive cycle of both species, to better specify the parameters of the spawner-recruit curve. Big skates have been suggested to be one of the most fecund elasmobranch species due to the presence of multiple embryos per egg case (Ebert et al. 2008). However, without specific data on the developmental time of embryos, and the number and timing of egg laying events per year, it is difficult to parameterize this information into a stock assessment model.

Despite these knowledge gaps, the development of age-structured population dynamic models for assessing two skate stocks in the GOA represents a step forward in our ability to manage these two species. Moving beyond the current Tier 5 abundance index-based assessment will allow management to build confidence in the stock status in the near term, and provide the basis for a more complete model in the long term, possibly leading to eventual increases in skate harvest. This study constitutes the first development of skate models in the GOA, relying on biological data collected during the course of both fisheries and fishery-independent research. Such data exist for many stocks in U.S. waters and efforts should be made to produce improved stock assessments (e.g., moving to a higher management tier) for these commercially harvested species as soon as possible to use the best available science for setting harvest levels. In this way, progress can be made towards fully assessing every stock in U.S. waters leading to better managed and more profitable harvest of our living marine resources.

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Table 2.1. Preferred model outputs for big and longnose skates.

Preferred Model	Unfished Biomass (mt)	Biomass in 2013 (mt)	MSY (mt)	B_{ratio} (2015)	Natural Mort., M	L_∞ (cm)	Von Bert. K
Big Skate	58,855	42,894	4,570	1.0395	0.256	185.1	0.12769
Longnose Skate	106,015	95,607	3,812	2.2969	0.246	162.1	0.06982

B_{ratio} = Current biomass/biomass at MSY
L_∞= Length at maximum age
Von Bert. K = Growth rate of the von Bertalanffy growth curve

Table 2.2. Comparison of outputs for a subset of models for big and longnose skates. Alternative model likelihoods are differences from the preferred model (negative values signify a higher likelihood associated with a better fit to the data). Parameter values and reference points are shown for the preferred model (italics). Numbers in bold for the alternative models signify outputs that are more than 50% different for life history parameters and reference points.

		Change in Negative Log Likelihood relative to Preferred				Life History Parameters			Reference Points			
	Model	Total likelihood	Survey index likelihood	Length comp likelihood	Size at age likelihood	Natural Mort., M	L_∞ (cm)	Von Bert. K	Virgin SSB (mt)	Bratio (2015)	Unfished Bio (mt)	MSY (mt)
Big Skate	Preferred	-	-	-	-	*0.26*	*185.1*	*0.128*	*8,925*	*1.04*	*58,855*	*4,570*
	Dome Selectivity	-25.0	-0.9	-16.0	-8.8	0.21	**300.0**	**0.063**	**23,344**	1.47	80,122	4,181
	σ_R = 0	-84.4	+0.2	+13.1	+0.9	0.24	183.2	0.130	9,218	1.13	57,773	4,254
	σ_R = 0.6	+6.5	-0.1	-4.5	-0.7	0.27	187.0	0.126	8,716	0.98	59,753	4,835
	Low Catchability	-3.9	-5.8	1.6	-0.1	0.28	186.2	0.126	**53,083**	1.38	**404,485**	**34,643**
	High Catchability	+83.4	+39.8	+44.5	-7.0	**0.40**	**300.0**	0.067	**2,422**	**0.38**	**17,162**	**1,991**
	Discard +1500 mt	+8.0	+5.2	+2.2	-0.8	0.26	187.9	0.125	9,998	0.98	64,517	5,041
Longnose Skate	Preferred	-	-	-	-	*0.25*	*162.1*	*0.070*	*1,951*	*2.30*	*106,015*	*3,812*
	Dome Selectivity	+24.7	+6.4	+10.1	-7.3	**0.05**	173.2	0.074	**21,253**	2.25	126,665	**1,650**
	σ_R = 0	+13.9	+9.2	+15.3	+0.5	0.24	162.1	0.070	2,316	**0.32**	118,138	**9,407**
	σ_R = 0.6	-24.0	-20.5	-14.1	3.6	0.21	152.7	0.079	1,423	1.24	60,128	4,308
	Low Catchability	-9.4	-7.7	-7.8	+6.2	0.22	150.0	0.082	**12,380**	2.78	**602,075**	**401**
	High Catchability	+43.8	+19.4	+27.2	-6.3	**0.40**	**269.5**	**0.030**	**364**	**0.26**	76,573	3,757
	Discard +1500 mt	+6.3	+3.4	+6.6	-4.7	0.29	182.8	0.056	2,133	**0.24**	158,136	**13,104**

L_∞ = Length at maximum age
Von Bert. K = Growth rate of the von Bertalanffy growth curve
Virgin SSB = Virgin stock spawning biomass
Bratio = Current biomass/biomass at MSY
SPRratio = ratio of the spawning potential ratio (SPR) as: (1-SPR)/(1-SPR at target fishing mortality)

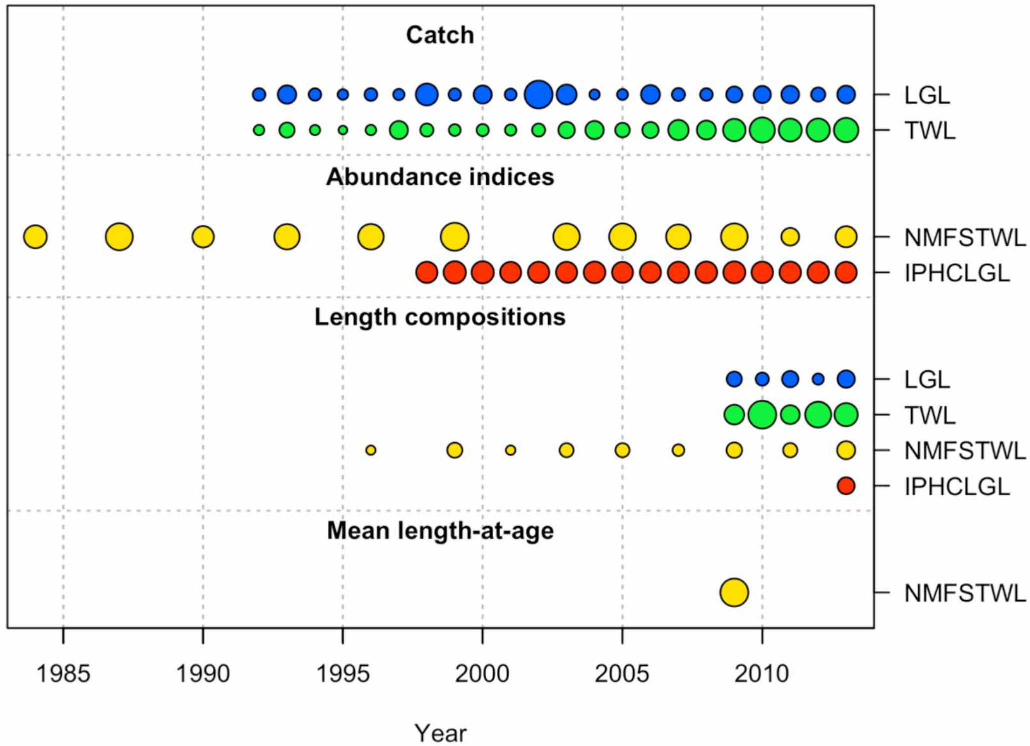

Figure 2.1. Data availability by year for each fleet. The size of the circle is proportional to volume for catches and proportional to precision for survey indices and length compositions. LGL = longline fishery, TWL = trawl fishery, NMFSTWL = NMFS trawl survey, IPHCLGL = IPHC longline survey.

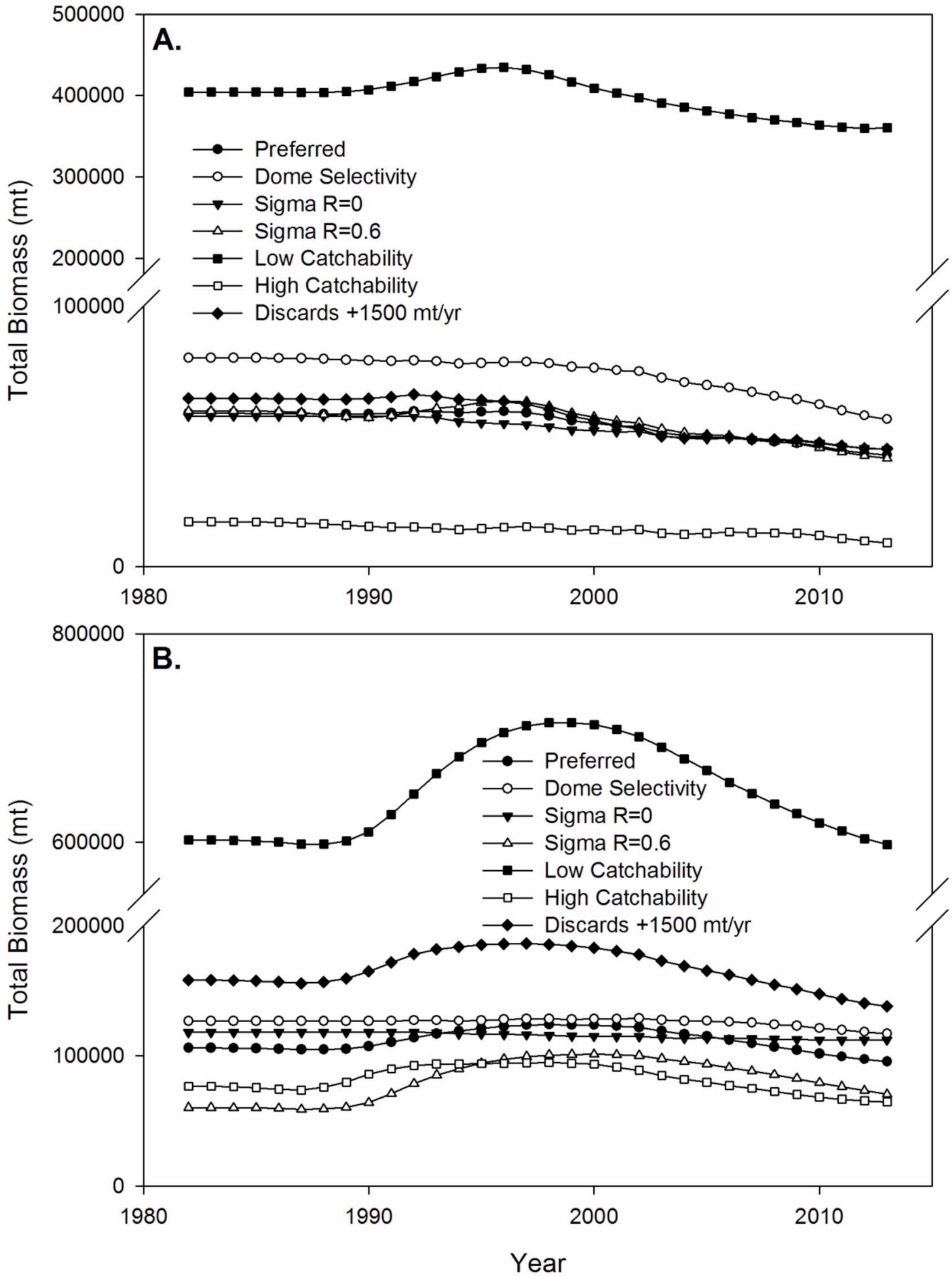

Figure 2.2. Time series of the total biomass of skates in the Gulf of Alaska. Biomass shown for big skate (A) and longnose skate (B) in the Gulf of Alaska over the data period for the preferred model (closed circles) and a select number of alternative models.

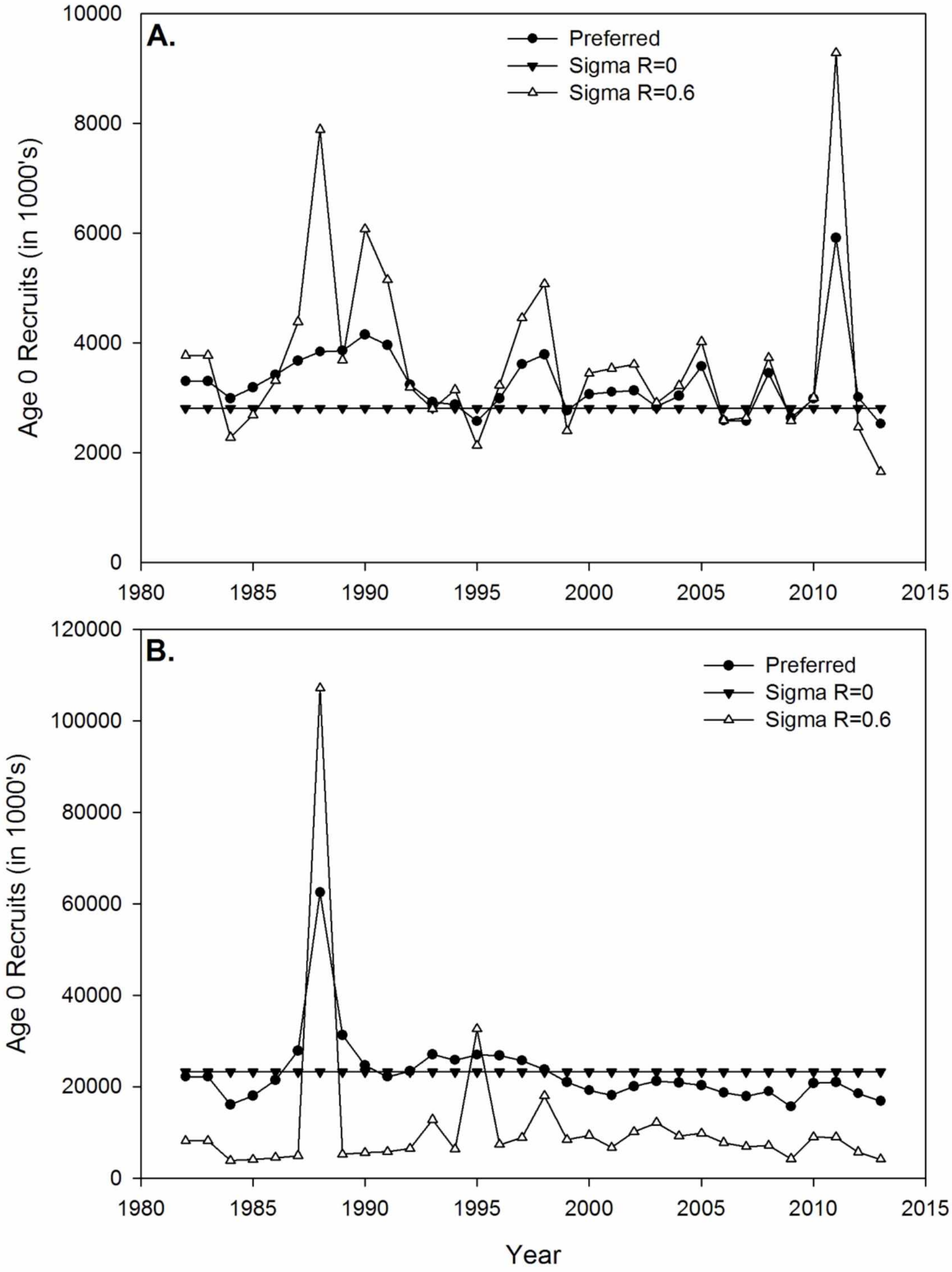

Figure 2.3. Time series of the number of age-0 recruits for skates in the Gulf of Alaska. Data shown for big skate (A) and longnose skate (B) over the data period for the preferred model with σ_R = 0.3 (closed circles), the model with σ_R = 0 (closed triangles), and the model with σ_R = 0.6 (open triangles).

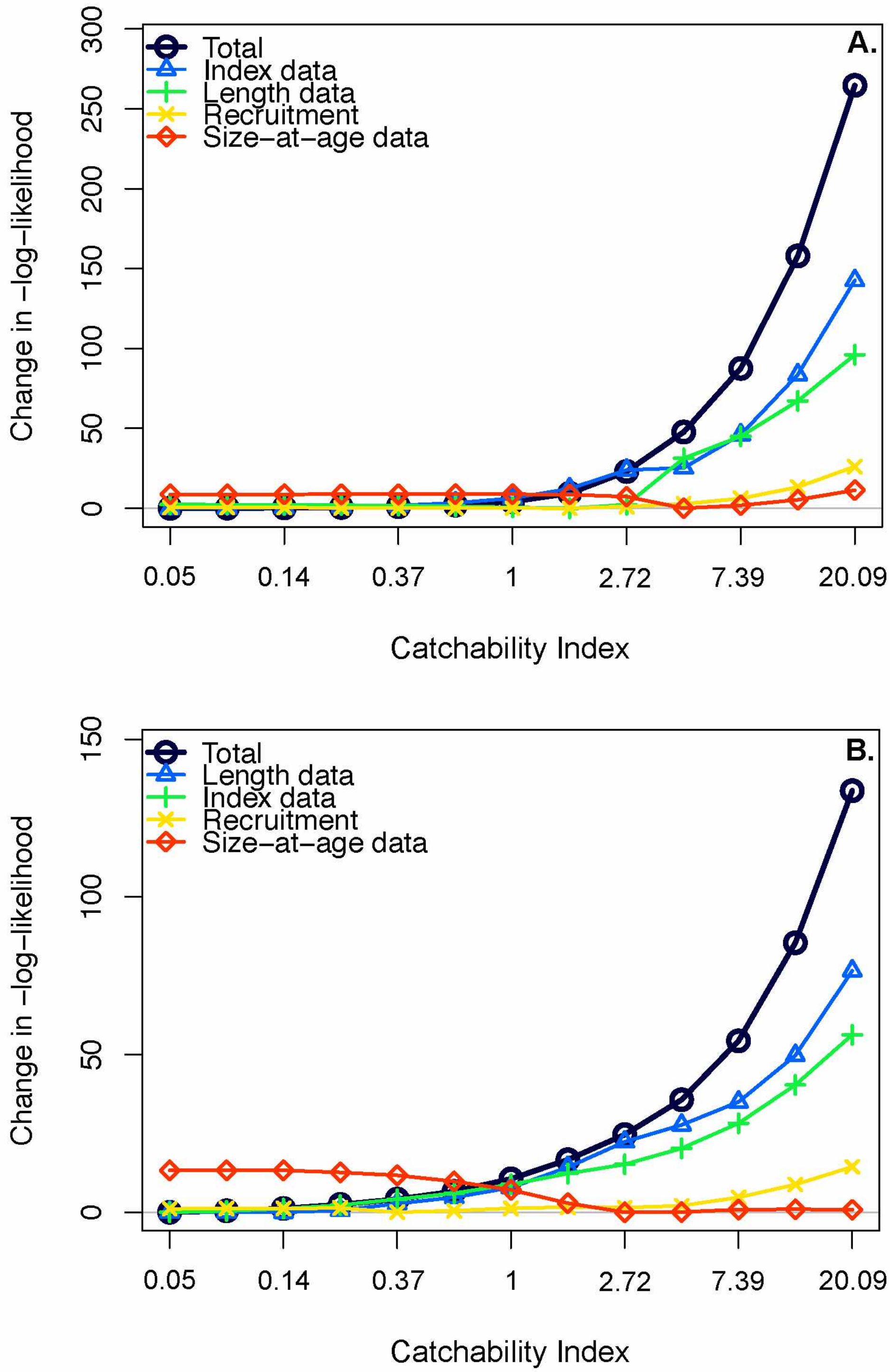

Figure 2.4. Catchability index likelihood for skates in the Gulf of Alaska. Data shown for big skates (A) and longnose skates (B), parsed out between total likelihood, length composition likelihood, survey index likelihood, recruitment likelihood, and size-at-age likelihood.

Chapter 3: A Bioeconomic Case Against Maximum Retainable Amounts in Ecosystem-Based Fisheries Management[4]

3.1 Abstract

The incidental catch of species other than those targeted by a fishery is commonly referred to as bycatch. When species are caught as bycatch, it can adversely affect their allowable catch in other fisheries in which they are targeted, and/or lead to overfishing or localized depletion of low productivity stocks. Bycatch can also cause socially unacceptable impacts such as mortality of charismatic species or perceptions of waste. Across world fisheries, there exist a wide variety of strategies for addressing the issue of bycatch. In the Gulf of Alaska (GOA), one of the primary bycatch management tools is the maximum retainable amount (MRA), which references the amount of bycatch that can be landed within a trip to the amount of target species being landed. This approach has potential detrimental consequences for both the health of the bycatch stock and the profitability of the target fisheries. We examine these consequences through the case study of skates in the GOA by applying a simple, constrained optimization bioeconomic model. Our results suggest a direct correlation between MRA and skate discards, and an inverse relationship between MRA and the number of fishing trips necessary to reach the total allowable catch (TAC). At an MRA of 20%, the model estimates skate landings to be 4,600 mt annually, for a revenue to the fishery of up to US$4,400,000 when prices are high. At an MRA of 5%, this decreased to 2,800 mt and a revenue up to US$2,640,000. Relaxing the current assumption of 100% discard mortality down to 50% delays the model-estimated time it takes to reach the TAC,

[4] Farrugia, T.J., Criddle, K.R., Seitz, A.C. *In prep.* A bioeconomic case against maximum retainable amounts in ecosystem-based fisheries management. North American Journal of Fisheries Management.

increases the amount of annual landings, and decreases annual discards. This study points to the ecological and economic inefficiencies of the MRA approach for skates, and we suggest exploring alternatives for bycatch management in the GOA.

3.2 Introduction

Fishery management agencies in the U.S. and around the world are making a push towards ecosystem-based fishery management (EBFM). The U.S. National Marine Fisheries Service (NMFS) defines EBFM as "a systematic approach to fisheries management that … recognizes the physical, biological, economic, and social interactions among the affected fishery-related components of the ecosystem … and seeks to optimize benefits among a diverse set of societal goals" (NMFS 2016). This holistic approach to managing marine living resources seems at odds with the more common management strategies that focus on only a few species at a time, called the "target catch", and encourage the lumping of all others into a single term, "bycatch". Bycatch is the incidental catch of fishes and invertebrates other than those targeted (Alverson et al. 1994; OECD 1997), for which the all-too-frequent remedy is discarding. It is our position that the concepts of "target catch" and "bycatch" are problematic in multispecies fisheries (i.e., fisheries that commonly capture and retain more than one species) because they are artificial regulatory constructs without ecological or economic meaning. Continued use of these terms may be a barrier to understanding the true nature of fisheries and the ecosystems on which they depend.

Bycatch can present a major sustainability concern in poorly managed fisheries (Kelleher 2005). Even in well-managed fisheries, bycatch of a particular species in a non-target fishery can adversely affect catch of that species in directed fisheries for it, lead to overfishing or localized depletion of low productivity stocks (e.g., Palof et al. 2010), and cause socially unacceptable impacts such as mortality of charismatic species or perceptions of waste. Concern about bycatch is reflected in the United Nations Food and Agriculture Organization (FAO) Code of Conduct for Responsible Fisheries, in sustainability certification standards such as those of the Marine Stewardship Council, and in U.S. federal law (FAO 2010). For example, the National Standard 9 in the U.S. Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA) stipulates that "Conservation and management measures shall, to the extent practicable, (A) minimize bycatch and (B) to the extent bycatch cannot be avoided, minimize the mortality of such bycatch."

Some fisheries employ highly selective gear and methods, or exploit unique temporal and seasonal aggregations, to target specific age classes of a single species (e.g., sac roe herring fisheries, dive fisheries). Because these fisheries are so targeted, the incidence of bycatch is very rare and there is little harm in treating such infrequent catches of other species as "bycatch" in those fisheries. In contrast, other commercial, artisanal, subsistence, and sport fisheries are better characterized as multispecies fisheries. In such fisheries, the composition of catches and landings can, in part, be influenced by fishers' decisions, which are influenced by management regulations, product prices, input costs, and expected catch rates. All of these factors are affected by choices of locations, time (season, day/night), gear (type, mesh size, escape ports, rollers), deployment methods (depth, speed, soak time), etc. Increased discards usually result from trying to adhere to multiple regulations on fish size, uneconomic mandatory landings requirements, seasonal closures, prohibited species caps and other limitations on the allowable composition of landings in multispecies fisheries.

When discards are high relative to captures, there is a cost to fisheries and ecosystems as a result of this institutionalized behavior of harvesting widely, but retaining narrowly (Bellido et al. 2011). Fish populations, habitats, trophic web structures, and vulnerable non-target species can all be impacted by high rates of discard mortalities. Although it has been argued that dead bycatch has more ecological value if it is discarded rather than landed (Heath et al. 2014), reducing bycatch and discards is almost universally seen as a fisheries management goal towards which to move (UN 2002). Under the current management regimes in the U.S., discarded bycatch is estimated to constitute over 10% of total catch (Benaka et al. 2014), with regulatory discards estimated to lead to millions of dollars lost in exvessel revenue, and billions lost in seafood-related revenue (Patrick and Benaka 2013). Efforts to increase retention of bycatch thus have the dual effect of reducing waste and increasing profitability of the fishing industry (Abbott 2007).

Bycatch management tools are an integral part of many fisheries management plans around the world. Some efforts to reduce bycatch are as simple as making gear modifications to exclude certain species from interacting with or being entrained in the fishing gear (Pascoe et al. 2010), or putting in place incentives to modify behavior of fishers (Baelde 2001; Abbott et al. 2015). Others require the creation of bycatch quotas and extensive electronic monitoring programs (Annala et al. 1991; Branch and Hilborn 2008, Stanley et al. 2014), even establishing quota markets to stabilize stochasticity in the amount and value of bycatch (Holland 2010). One of the most intricate tools for managing bycatch involves the use of Pigouvian taxes, or deemed values, to provide the proper incentives for fishermen to match their catch to their bycatch quota (Walker and Townsend 2008).

An alternative approach to bycatch minimization treats bycatch as a technological problem, wherein the imperfect selectivity of fishing gear sets a lower bound on the minimum amount of bycatch needed to allow the target fishery to harvest its total allowable catch (TAC). One such tool is setting a maximum retainable amount (MRA) on bycatch, calculated as the percentage (in weight) of various species allowed to be retained, relative to the weight of the highest-volume target species retained on board during one trip (Ackley and Heifetz 2001). As they fish, vessels must estimate the weight of the various species, as they will only be able to sell bycatch up to the MRA for each bycatch species. In some instances, vessels may incur a penalty for landing more bycatch than allowed under the MRA. In effect, catches in excess of the MRA will likely be discarded. Although MRAs do not prevent bycatch, they limit the extent to which harvesters stand to benefit from retaining bycatch, thereby reducing the incentive to fish in areas or at times when high bycatch rates are likely. But this incentive can be dampened if those areas and times also provide elevated catches of target species and/or are nearer to port. Generally, the MRAs are also coupled with an annual TAC for the bycatch species. Once the TAC for a bycatch species is reached, it becomes a “prohibited” species and cannot be retained for the remainder of the fishing season.

3.2.1 Case Study: Skates in the Gulf of Alaska

The MRA management scheme described above is applied to skate species (family Rajidae) in the Gulf of Alaska (GOA) groundfish fisheries (Ormseth 2016). Skates are in high-demand in global seafood markets and are supplied from catches taken in European, North American, South American, and East Asian waters (Clarke and Dent 2015). Although there is relatively little domestic demand, the United States lands around 25,000 metric tons (mt) of skates (round weight) per year, and exports 5,000 mt of processed skate product with a gross value of >US$11 million annually (NMFS 2015a). Over 90% of U.S. landings are exported to Asia and Europe (NOAA Fisheries Office of Science and Technology 2015). Although poorly documented, there are suggestions that during the 1970s and 1980s, circular punch-cuts of U.S. skates were sold as scallops in domestic markets. We have been unable to find evidence that this took place on a commercial scale with skates, although it may have happened with manta ray (*Manta spp.*) wings (Booda 1994; Rubin 2002).

In the GOA, skates are captured primarily in bottom trawl and longline gear, most often by vessels targeting Pacific cod (*Gadus macrocephalus*), Pacific halibut (*Hippoglossus stenolepis*), sablefish (*Anoplopoma fimbria*), arrowtooth flounder (*Atheresthes stomias*), and other flatfishes (Ormseth 2016). Despite the MRA limits imposed on skates as non-target species, total catches of skates have averaged >4,000 mt per year in the GOA between 2005 and 2016, comprised primarily of big skate (*Beringraja binoculata*) and longnose skate (*Raja rhina*). Skates have an exvessel value between US$0.35 and US$0.95 per kg, which at times represents twice the price per weight of target species such as Pacific Cod. In addition, skates' nutritional content and low heavy metal contaminant loads compared to other commercial species make them a desirable, marketable product (Farrugia et al. 2015).

As mandated in the MSFCMA, the scientific and statistical committee (SSC) of the North Pacific Fishery Management Council (NPFMC) sets annual overfishing level (OFL) and allowable biological catch (ABC) values for GOA skates, with the latter serving as an upper limit for the TAC set by the NPFMC. Because there is limited information on life history parameters and stock structure, the SSC sets OFL and ABC under "Tier 5" management, meaning that the only information available are estimates of biomass and natural mortality (NMFS 1999). With more information and a formal stock assessment model, GOA skates could be raised to "Tier 3," which uses estimates of biomass and fishing mortality reference points and could allow for an increase in the ABC (Figure 3.1). The added information represented by moving from Tier 5 to Tier 3 reduces the perception of risk and increases our confidence in the stock assessment, potentially allowing for more liberal quotas. A subsequent increase in ABC would translate to an overall increase in the value of the fishery. For example, if the big skate stock size was estimated at 50,000 mt, the Tier 3 management scheme would yield an ABC that is 500 mt greater than the ABC under Tier 5, a potential added gross value of between US$175,000 and US$475,000. The added net value would depend on how this added yield is harvested.

Until recently, the MRA for GOA skates was 20% — meaning that up to 200 kg of skates could be retained for each 1,000 kg of target species (e.g., Pacific cod *Gadus macrocephalus*) retained. In 2016, the NPFMC reduced the GOA skate MRA to 5% (e.g., 50 kg of skates per 1,000 kg of Pacific cod) to reduce the possibility that the skate TAC would be reached early in the year (NPFMC 2015). However, while a lower MRA may slow the rate of landings, it may also lead to increased regulatory discards, in effect transforming dead skates landed for human consumption into dead skates discarded at sea.

Discard and retention rates are difficult to estimate for GOA skates because fisheries observers were deployed on only 30% of vessels between 18.3 and 37.8 m length overall that were responsible for much of the skate catch, and the coverage is uneven among fisheries (Stevenson and Lewis 2010). In addition, the observer coverage was restructured in 2013, which increased the number of small boats and boats participating in the Pacific Halibut Individual Fishing Quota (IFQ) program covered by observers (NMFS 2015b). Nevertheless, estimates of skate retention rates are available from the NOAA Alaska Regional Office, and over the last 10 years, they have ranged between 15% and 93% for big skates and between 28% and 74% for longnose skates (Ormseth 2016).

Post-capture discard mortality of skates in commercial fisheries varies substantially based on species, depth, gear, and handling (Ellis et al. 2017). In trawls, mortality ranges between 25% after 14 hours (Benoît et al. 2012) and 60% after 7 days (Mandelman et al. 2012), with many studies reporting around 50% mortality after 48 hours or more (Enever et al. 2009; Rudders et al. 2015). Fewer studies have been conducted on skates caught with longlines, though Endicott and Agnew (2004) found a 57% mortality after 12 hours, and Ellis et al. (2008) observed no at-vessel mortality when the skates were unhooked manually. However, because the NPFMC does not have reliable species-specific estimates of discard mortality rates for big and longnose skates, 100% discard mortality is assumed as a precautionary approach.

The interaction between management measures, fishing behavior, and discard mortality can become complicated to the point where consequences of regulations may be difficult to anticipate. This study develops a simple bioeconomic simulation-optimization model to examine the economic impact of changes in MRA on the profitability of skate fishing and fishing strategy. The model was structured as a constrained optimization, a mathematical process that involves maximizing a benefit function or minimizing a loss function with respect to choice variables while reflecting physical, biological, and technical constraints on admissible values of those variables. Constrained optimization models have been extensively applied to fisheries, including determining maximum sustainable yield (MSY) to analyzing catch-at-age data (Liu 1995), making decisions about fish habitat restoration (O'Hanley et al. 2013), balancing catch and bycatch in mixed species fisheries (Brown et al. 1979; Murawski and Finn 1986; Larson et al. 1996), and optimizing the value of a suite of product forms produced by seafood processors (Kasilingam 1995; Larkin et al. 2003).

To our knowledge, this is the first explicit use of constrained optimization to examine the impact of fishery management decisions on the profitability and sustainability of a high value, non-target species. That is, we examined the bioeconomics of the non-target species, rather than optimization of the value of a target species subject to technological limitations and caps on the bycatch species. The model provided insights into the economic and ecological consequences of using an MRA approach as a tool to regulate skates as non-target catch in other GOA fisheries. The case study of GOA skates was then used to describe the concerns with, and alternatives to, the MRA approach.

3.3 Methods

Information on skate prices, catches, and landings were used to inform our analysis of the skate fishery in the GOA. Costs associated with harvesting skates in the GOA are confounded with the costs of harvesting other species, making them difficult to calculate. Instead, the model focused on describing the revenue from harvesting skates. Exvessel and first wholesale prices of skates from 1995 to 2015 were obtained from the Alaska Department of Fish and Game (ADFG) Commercial Operator's Annual Report (COAR, database accessed January 31, 2017). Prices were adjusted for inflation to a 2015 base, using the consumer price index for all urban consumers for all items (data from the U.S. Department of Labor, Bureau of Labor Statistics).

Skate catches from 2010 to 2016 were obtained from the NMFS Catch Accounting System (CAS, database accessed on March 16, 2017). Annual catches in metric tons (mt) were parsed out by either NMFS area, sector (catcher vessels vs. catcher/processors), or target species individually, to avoid confidentiality issues that could arise from excessively partitioned data. In addition to the weight of skates retained, the CAS database yielded the number of trips in which skates were caught, the corresponding total landed weight of target species caught during those trips, and the number of vessels that participated in the skate harvest. These data were then used to calculate the average percentage per trip of the catch that was composed of skates. For this analysis, all skate species were aggregated including big skate, longnose skate, Alaska skate (*Bathyraja parmifera*), Aleutian skate (*Bathyraja aleutica*), whiteblotched skate (*Bathyraja maculata*), and “other” skates.

A simple bioeconomic model was used to examine how biomass-driven variations in OFL and ABC, and the management choices of MRA would affect the number of trips needed to land the skate TAC, the revenue generated from skates and the harvest strategy of skates by the fishing industry. The model consisted of two components: 1) a constrained optimization (Sun and Yuan 2006) on the number of trips required to catch the TAC under different MRAs; followed by 2) a model of discards under each scenario. Together, these models provided estimates of skate harvests over the course of a season, the total amount of discards, and the associated value gained or lost under different MRAs.

The inputs for the optimization component included: the TAC; the fishing mortality at the overfishing level F_{OFL} defined by the current Tier 5 management (0.1); and *Biomass*, the total weight of skates present in the GOA estimated using a Stock Synthesis-based population dynamics model (Farrugia et al. in prep). Additionally, our model used inputs for MRA, in percent of the total catch that can be composed of skates, and C_{MRA}, the weight of skates usually landed for each percent of skate retention (calculated from the CAS catch data described above). The two variables estimated by the optimization are *landings*, the total amount of landings of skates per year, and *trips*, the total number of vessel trips that can catch skates per year.

The loss function, L, to be minimized by the optimization was defined as:

$$L = \alpha * \left(e^{1} - e^{\left(\frac{landings}{TAC}\right)}\right)^{2} + \beta * trips \tag{3.1}$$

where α and β are constants that can be ranged to reflect the relative importance of opportunity costs and variable trip costs. Constraints on this optimization included:

$$0 \leq landings \leq F_{OFL} * Biomass \tag{3.2}$$

and

$$\frac{landings}{trip} \leq MRA * C_{MRA} \tag{3.3}$$

For *Biomass*, the initial parameter value was the output of the stock assessment biomass for big and longnose skates in the GOA of 140,000 mt (Chapter 2). The *TAC* was set using the current NMFS Tier 5 approach as *Biomass* multiplied by 0.75 * F_{OFL} (Ormseth

2016). This yielded a TAC of 10,500 mt. Finally, we set C_{MRA} = 350 kg per percent of MRA based on CAS catch data (Table 3.1). Here, we assumed that no discards were taking place, and that fishermen were perfectly able to scale their skate catch to the MRA (i.e., the fishermen would catch exactly the amount of skates allowed under the MRA and retain all of it).

This first step of the model was coded in R (R Core Team 2014) using the Rsolnp package (Ghalanos and Theussl 2015). This solver implements an augmented Lagrange multiplier, based on algorithms developed for linearly constrained non-linear programming (Ye 2013). The R package was embedded within a for-loop to allow the optimization to be performed automatically over a range of values for parameters of interest (i.e., MRA or biomass).

The second step of the model involved extrapolating the results of the constrained optimization to get a more complete model of the fishing behavior by including discards. The number of trips required to land the TAC estimated at each level of the MRA in step 1 was used to calculate the slope of the relationship between the number of trips and the skate landings. For each MRA:

$$landings\ slope = \frac{landings}{\#\ trips} \tag{3.4}$$

It was assumed that this relationship was linear (i.e., the weight of the landed skates increased linearly with the total number of trips).

Using the average retention estimates from the CAS, we assumed an average skate retention rate of 0.45 when the MRA was 20% (2010 – 2015) and an average of 0.27 when the MRA was 5% (2016). With these two estimates, we constructed a linear relationship between the MRA and the expected average retention rate:

$$retention\ rate = 0.012 * \text{MRA} + 0.212$$

Applying the MRA-specific retention rate to the landings, we could then estimate the total weight of skates caught per trip throughout the season, and therefore the amount of discards:

$$catch\ per\ trip = \frac{landings}{retention\ rate} \quad (3.6)$$

$$discards = \ catch - landings \quad (3.7)$$

The total amount of catch, landings, and discards were then simulated throughout the progression of a fishing season at different MRAs. For each trip, we assumed that the fishermen would retain and land the maximum amount of skates and discard the rest. Both landings and discards counted against the TAC, therefore vessels would retain skates until the overall TAC for the season was caught, after which all skates would be discarded as prohibited species (NPFMC 2015). After that time, any additional trips would have no landings and all catch would be discarded. It was assumed that fishing behavior did not change substantially after the TAC was reached, since fishermen would still be targeting their original target species.

The fishing season was simulated under 1) the assumption of 100% discard mortality (currently assumed by NMFS), and 2) a 50% discard mortality (based on the primary literature). It was assumed here that the catch rate of skates per trip would remain constant even after the TAC was reached. Finally, the total number of trips and total weight of skate catch, landings, and discards were estimated for each value of MRA at the end of the season. The corresponding value of the landed skates and lost value of discarded skates was calculated.

3.4 Results

After adjusting for inflation, the average exvessel price for skates increased from US$0.30 per kg round weight in 1995 to over US$0.94 per kg round weight in 2015, a 205% increase in price (Figure 3.2). Similarly, after adjusting for inflation, the first wholesale price for skates rose from an average of US$1.16 per kg in 1995 to US$3.48 per kg in 2015, a 197% increase over the same 20 years (Figure 3.2). Interestingly, over this period, processors have experienced greater price variability than harvesters (Figure 3.2).

Although skate catches have been increasing overall since the 1990s (Ormseth 2016), landings of skates have declined from 2,771 to 1,279 mt during 2010–2016 (Table 3.1). This harvest was accomplished through an average of 1,825 fishing trips per year, undertaken by about 300 vessels fishing throughout the GOA. Harvesters landed between 0.68 and 1.56 mt of skates per trip. On average, for each percent of skate retention, harvesters were landing 0.35 mt of skates per trip.

The surface of the objective function increased linearly as the number of trips increased, but nonlinearly with respect to variations in the amount of landings (Figure 3.3). The initial optimization, which did not include discards, attempted to minimize the number of trips and chose an intermediate level of landings, so that landings equaled the TAC. The MRA constraint restricted the optimization from reaching the lowest areas of the surface;

and, as might be expected, an MRA of 5% was more restrictive than an MRA of 20% (Figure 3.3C). When discards were not taken into account (i.e., only skates allowed to be retained under the MRA were caught and landed, and none were discarded), landings always matched the TAC very closely (Figure 3.4). Only at very low values of MRA was there a slight difference between TAC and landings, due to the number of trips that would have been necessary to harvest the full TAC, which imposed a penalty on the objective function. The number of trips necessary to land the TAC showed a decreasing power relationship with MRA, indicating that at very high levels of MRA (such as during a hypothetical directed fishery) very few trips are necessary to land the TAC.

Integrating discards into the model changed the picture substantially, because discards were counted against the TAC. Importantly, our model assumed discards were being perfectly observed, or correctly extrapolated for unobserved trips. Therefore, even if very few skates could be retained per trip, as long as they were being caught and discard mortality was assumed to be 100%, they counted against the TAC and effectively shortened the skate season. For example, at an MRA of 5%, the model estimated that it would take about 1,230 trips to catch the TAC (Figure 3.5A). After that many trips, harvesters would be expected to have landed about 2,800 mt of skates, but would have had to discard more than 7,400 mt. In contrast, at an MRA of 20% (Figure 3.5B), the TAC would be reached after 510 trips, by which time landings would be about 4,600 mt, with 5,550 mt of skate discarded. Finally, if the MRA were doubled to 40% (Figure 3.5C), only 400 trips would be needed to reach the TAC, yielding 7,000 mt of landings and 3,300 mt of discards.

However, if once the TAC is reached, fishing behavior does not change and the same rate of skate catches is maintained, the rate of discarding accelerates (Figure 3.5). After a nominal fishing season of 1,500 trips, MRAs of 5%, 20%, and 40% would yield total discards of 9,700 mt, 25,300 mt, and 31,900 mt, respectively. If vessels were able to stop catching all skates once TAC is reached, the higher MRAs would be more efficient at landing the most skates in the smallest number of trips, and with the least amount of discards. However, if skate catch were to continue despite the TAC having been reached, discards would continue to increase for the remainder of trips.

If discard mortality is no longer assumed to be 100%, but instead we use the overall 50% average discard mortality, the patterns remain similar, but the season length and overall landings are increased. Indeed, if only half of the discarded skates are counted against the TAC, it will take more trips to reach the TAC, and therefore more landings can be accumulated before skates become prohibited (Figure 3.5). In fact, at an MRA of 5%, the TAC is not even reached after 1,500 trips, by which time 3,400 mt of skates have been landed and 9,000 mt discarded (Figure 3.5D.). At an MRA of 20%, skate retention would be allowed to continue for 700 trips before TAC was reached, by which time 6,350 mt of skates would have been landed, and 7,600 mt discarded (Figure 3.5E.), while at an MRA of 40%, skate retention would continue for 460 trips, for a total of 8,350 mt in skate landings and 3,600 mt in discards (Figure 3.5F.).

The total weight of skate landings at the end of a simulated 1,500-trip season increased with MRA, until an MRA of about 65%. At this level of MRA, all skates taken in each trip could be retained and the TAC was reached in 347 trips, assuming 100% discard mortality (Figure 3.6). Correspondingly, the amount of skates discarded until the TAC was reached decreased with decreasing MRA levels until 65%, after which the model estimated that there would be no more discards. However, if fishing behavior did not change after the

TAC was reached, catch would continue at the same level, and all skates would be discarded, which would greatly increase the discard rate (Figure 3.6).

Economically, increasing the MRA allows more value to be landed and requires less to be discarded. With skate exvessel prices between US$350 and US$950 per mt, the value of skate landings decreased from between US$1,624,000 and US$4,400,000 to between US$973,000 and US$2,640,000 given changes in the MRA from 20% to 5%. In addition, the value lost through discards increased from between US$1,947,000 and US$5,286,000 to between US$2,598,000 and US$7,052,000. Although a decrease in MRA also increased the number of trips to reach the TAC, this was not considered here as an economic factor because skates are not the target of fishing trips, so trips would be taken to target other species, regardless of the situation with skates. In addition, if it is assumed that discard mortality was only 50% rather than 100%, the estimated value of landings with a 20% MRA is increased from US$4,400,000 to over US$6,000,000.

3.5 Discussion

The GOA skate fishery presents an interesting case study in which valuable commercial skate species are being harvested while fishing for at least six different target species or species complexes. Although both exvessel and first wholesale prices for skates have increased at similar rates in the past 20 years, first wholesale prices have been more variable than exvessel prices. The data suggest that fishermen have accepted an increased spread between exvessel and wholesale prices, in exchange for processors accepting a larger portion of the price risk. Once fishermen have caught and landed skates, they have little influence on the value of their harvest. The wholesale price of skate is being dictated by global markets for skate, ray, and shark meat, of which skates from the GOA only represent about 2% of the total weight and 1% of the total value traded (Clarke and Dent 2015). Therefore, changes in the supply of skates from the GOA are unlikely to affect global prices, and wholesale prices for GOA skates will track global market fluctuations.

The MRA, the principal management mechanism for regulating the catch of skates in the GOA, was intended as a way of slowing skate harvest rates. Slower harvest rates were desirable due to conservation concerns for skates and economic concerns for fisheries in which the limited availability of a valuable bycatch species might induce a race-for-bycatch, leading to underharvest of target species such as Pacific Cod (NPFMC 2015). However, the slowing of skate harvest rates can alternatively be accomplished by increasing the number of trips over which the harvest can take place, as shown by our model. Decreasing the MRA also distributes the amount of harvestable skate biomass among more trips: a change in MRA from 20% to 5% in 2016 has more than tripled the number of trips needed to harvest the skate TAC. Potentially, this could also result in more vessels having access to the skate TAC, although that pattern has not emerged in the first year of lower MRA.

As a secondary consequence however, changes in the MRA also directly impact the discard rate of skates. Although fishermen may be able to adjust their catch rates of certain species, it is unlikely that they can avoid capturing bycatch species, such as skates, while fishing for species like Pacific cod, sablefish (*Anoplopoma fimbria*), or Pacific halibut (*Hippoglossus stenolepis*). Therefore, a decrease in the MRA for skates will lead to an increase in the skate discard rate. This in turn impacts the value of the fishery, as discarded skates count against the TAC without providing economic benefit. There is some evidence that discards provide an ecological benefit through cascading food web effects (Heath et al.

2014), but even more ecological benefit is achieved through the reduction of bycatch in the first place, and these benefits need to be weighed against other biological, economic and policy goals (Luk and Pritchard 2009).

Our model also clearly showed the influence of the 100% discard mortality assumption. The value of the fishery increased by 36% when it was assumed that only half of the discarded skates ended up dying, compared to an assumption of 100% mortality. Although 50% discard mortality seems like a reasonable alternative assumption for GOA skates, actual discard mortality rates depend on the specific fishing conditions and species involved (Ellis et al. 2008). Given the sensitivity of the model outcomes for landings and value to changes in the assumed discard mortality, a precautionary approach is warranted. It would therefore behoove both management and the fishery to better understand the long-term discard mortality rates of skates in the GOA, through studies such as those done with trawl gear by Mandelman et al. (2012) and with longline gear by Endicott and Agnew (2004).

Other simplifying assumptions were made in our model, specifically regarding the behavior of fishermen. This was due to some difficult-to-estimate restrictions on fishing activities, such as the quality of the fishing on any given trip, the amount of space left in the fish hold, and the duration of the fishing trip. We assumed one average retention rate across all vessel sizes, gear types, and target species. In reality, modeling the opportunistic behavior of fishing on skates would require modeling the full suite of species, vessels, and gear types in these multispecies fisheries, but this would quickly become excessively complicated and over-parameterized (Hudson and Reuman 2013). Such an approach was also beyond the scope of the present study, which attempted to more simply determine the direct impact of a specific management decision (setting an MRA) on skate catch and profitability.

Further, although we attempted to model the behavior of fishermen after the TAC was reached, this was also difficult to describe. We instead modeled the two extremes: assuming either that there was no change in catch rate after the TAC was reached, or that the fishermen were able to reduce their skate catch to zero after the TAC was reached. The reality is most likely that fishermen can reduce their skate catch to some degree through choice of fishing location and gear deployment method. But they may not be able to eliminate skate catches altogether while continuing to participate in Pacific cod, Pacific halibut, sablefish, and flatfish fisheries. In addition, changing fishing behavior to avoid skates may entail opportunity costs if those changes also mean moving away from preferred fishing grounds for target species. Moreover, without sufficient incentive to reduce skate bycatch, fishermen may not change their behavior once the TAC is reached, even if they were able to do so (Baelde 2001, Pascoe et al. 2010, Abbott et al. 2015).

In reality, there are at least two major incentive structures for harvesting skates in the GOA. On one hand, the highest valued use of allowable skate landings might be as a "choke" species that allows pursuit of other fisheries until skates become prohibited. Delaying that point of prohibition would permit more harvest of the targeted resource. For example, at an MRA of 20%, each mt of skate catch allows harvest of 5 mt of Pacific Cod; while at a reduced MRA of 5%, each mt of skate catch would allow harvest of 20 mt of Pacific Cod. These fisheries "use up" small amounts of skate TAC scattered over an extended season, but a higher MRA may lead to early exhaustion of the TAC, before the rockfish and Pacific Cod TACs are reached, due to a race-for-bycatch (Smith 1993; Abbott and Wilen 2011). On the other hand, other vessels in the GOA fishing fleet want to establish a targeted skate fishery, and are therefore unconcerned with the ancillary value of skates as a choke species, instead wanting to most quickly and efficiently catch the skate TAC. In our analysis, this was represented by having an MRA of 100% and led to only 321 trips being necessary to harvest the TAC. Although this is unlikely to be an exact prediction of what would happen under a targeted fishery situation, it is probable that the TAC would be reached very quickly and a "race for skates", in which skate harvest would only benefit the first harvesters to catch and retain skates, could emerge.

Balancing these two desired harvest strategies cannot be accomplished by adopting a single MRA level. It is a truism that it is impossible to optimize more than one objective with a single policy instrument. As shown by our model, lowering the MRA allows more trips to retain skates, but at the cost of reduced landings per trip and overall landings for the season. Beyond skates in the Gulf of Alaska, MRAs may still be useful to nudge fisherman behavior in fisheries with very little bycatch on the rare occasions when non-target or prohibited species are caught. But MRAs make little sense in a multispecies fishery where at least two, and often more than two, species are regularly captured, especially when high discard mortalities are assumed. By definition, multispecies fisheries cannot target only one species, so MRAs will inevitably lead to discards, increased mortality and lost economic opportunities, as we have shown here, or to underharvest of the bycatch species when the abundance of one or more target species declines.

These consequences seem to make MRAs antithetical to approaches like EBFM, which promise in part to increase sustainability, decrease waste, and explicitly address all parts of a fishery and not just the target species. Other than being economically wasteful and socially undesirable (Pascoe 1997), MRAs are in direct conflict with major U.S. federal fisheries policy, namely the Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA) National Standard 1 (NS1). NS1 compels management to prevent overfishing while providing the greatest overall benefit to the nation (Federal Regulation Title 50, Chapter 6, §600.310). Our case study suggests MRAs are at minimum inefficacious, pushing fishermen to discard catch that took time and resources to capture, and in some cases may actually increase the risk of overfishing. When discards count against a fisherman's quota, there is an incentive not to report them, and without 100% observer coverage, catch may be severely underestimated leading to overharvesting. This would clearly not be in the best interest of the industry, the ecosystem, or the nation.

Furthermore, the binary concept of a particular species being either "catch" or "bycatch" in multispecies fisheries is problematic, ultimately acting as a barrier to fully understanding and managing fisheries and ecosystems. For example, when the MRA is defined in terms of a reference stock, such as Pacific cod, a decrease in the reference stock will mean a proportionate decline in catches of valuable, non-target species, such as skates and rockfish, even though stocks of those species have not declined. As a result, regulatory discards will increase whenever the estimated biomass of the reference species declines. Instead, a different approach is required; perhaps one that includes individual or cooperative catch shares allocated through an annual auction and freely tradable across sectors. Under such a strategy, vessels targeting other high value species could hoard their skate shares to enable associated catches of Pacific cod and Pacific halibut, while other fishermen could exercise their shares in intensely focused skate trips.

One of the most straightforward alternative approaches to MRAs, which could be applied to management of skates in the GOA, is mandatory landings. In this approach, all catch, or at least all catch with commercial value, is required to be landed (i.e., a discard ban). This approach has been applied in the Norwegian fleet of the North Sea fisheries since 1987 with considerable success (Diamond and Beukers-Stewart 2011) and has been integrated into the European Common Fisheries Policy. Another approach would be a catch share program that includes both individual fishing quotas (IFQ) and individual bycatch quota (IBQ), such as the one employed by the U.S. West Coast groundfish trawl fishery (PFMC and NMFS 2010). This has led to the reduction of Pacific halibut bycatch in the trawl fishery (Jannot et al. 2015), but economic modeling has also suggested that transferable quotas for target and bycatch species simultaneously can create the correct economic incentives to maximize the value of the fishery (Boyce 1996). Finally, in 2001, New Zealand instituted a deemed value system in its fisheries, which taxed catches that were in excess of the quota (Peacey 2002). This is essentially a Pigouvian approach (Baumol 1972), which offsets the negative externalities of bycatch and discards and produces an incentive to keep all commercially valuable species by facilitating quota transfers (Walker and Townsend 2008). We suggest that managers examine how these three alternatives could be applied to GOA skates in place of the current MRA system.

Fishermen in the GOA are confident that skates will remain a valuable species for the foreseeable future, and are therefore interested in maintaining their access to as much of the skate resource as possible (Julie Bonney, Alaska Groundfish Data Bank, pers. comm.). The ultimate problem is one of allocation of a resource, in this case the skate TAC, and how to allocate that resource while ensuring that it does not lead to larger economic or ecosystem costs. In general, managing discards can be a complex and unwieldy problem, and much time and effort has been spent on ways to address it (Hall and Mainprize 2005). It is one of the critical issues of fisheries management today, and will likely remain so for the foreseeable future (Bellido et al. 2011). Solutions will need to be tailored to the specific social-economic and ecosystem conditions of each region, and management strategies will need to be properly modeled and evaluated, and rejected when they are shown to be suboptimal. Our study has pointed out the inherent flaws of the MRA approach for GOA skates, and we suggest fisheries managers would do well to examine alternatives that may better take advantage of the economic value of skates while also reducing the ecological impact of skate bycatch.

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Table 3.1. Landings of skates and target species, vessel trips and percent retention of skates (in weight) caught in the Gulf of Alaska.

Year	Skates (mt)	Target (mt)	# Trips with skates	# Vessels	Skates per Target (%)	Skates per Trips (mt)	Skates (mt) per % Retention*
2010	2,771	66,384	1,837	345	4.17	1.51	0.36
2011	2,755	58,901	1,765	337	4.68	1.56	0.33
2012	2,737	60,302	2,199	397	4.54	1.24	0.27
2013	2,356	56,960	1,679	355	4.14	1.40	0.34
2014	1,457	70,406	1,834	338	2.07	0.79	0.38
2015	1,341	71,941	1,959	303	1.86	0.68	0.37
2016	1,279	62,750	1,500	297	2.04	0.85	0.42

* The weight of skates per % of retention is used as a proxy for the value of C_{MRA} in the constrained optimization model.

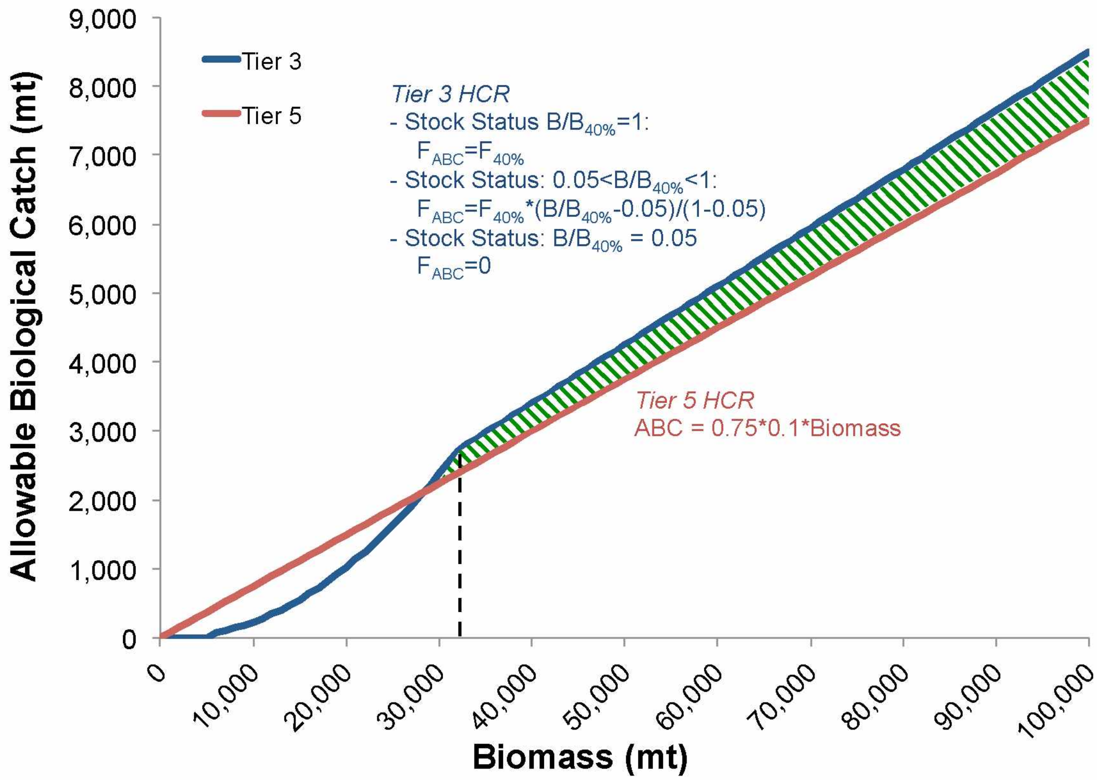


Figure 3.1. Allowable biological catch (ABC) at different levels of biomass for big skates in the Gulf of Alaska under two different management tiers. The green hashed area represents the value of increasing the management tier. The black dashed line represents the biomass at which the Tier 3 harvest control rule (HCR) changes, and the Tier 3 management no longer offers a benefit. Data to produce this figure was taken from the stock assessment model developed in Chapter 2.

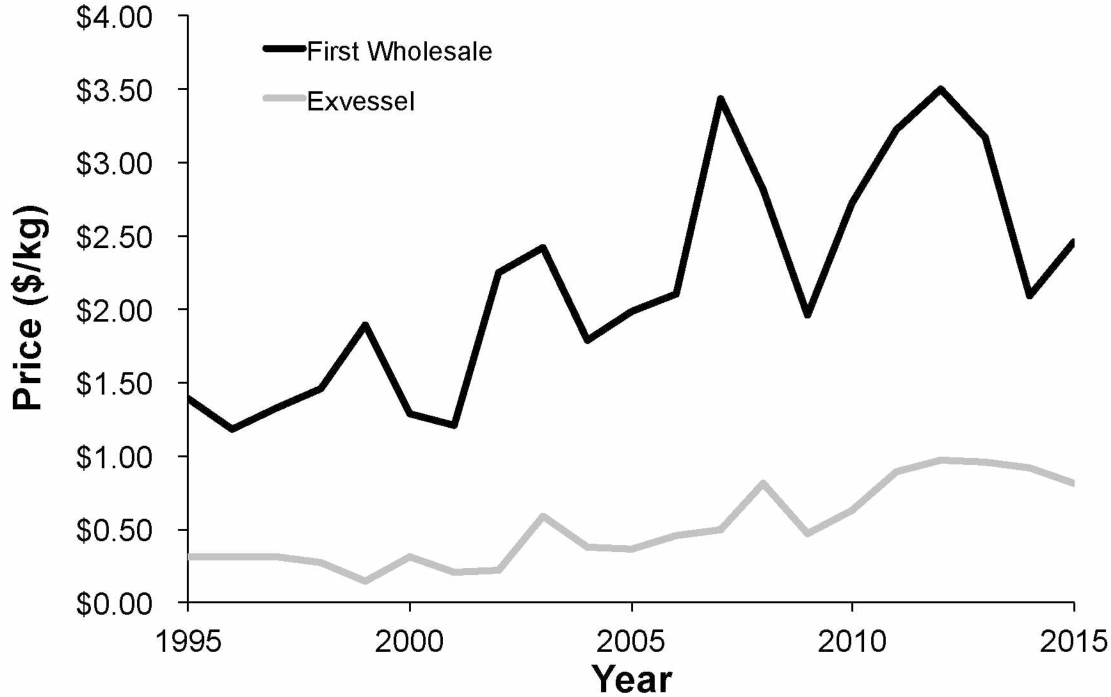


Figure 3.2. Exvessel and wholesale prices (US$/kg) for skates landed from the Gulf of Alaska. Prices are adjusted for inflation to 2015 dollars using the consumer price index. Data come from the Alaska Department of Fish and Game Commercial Operator's Annual Report (COAR).

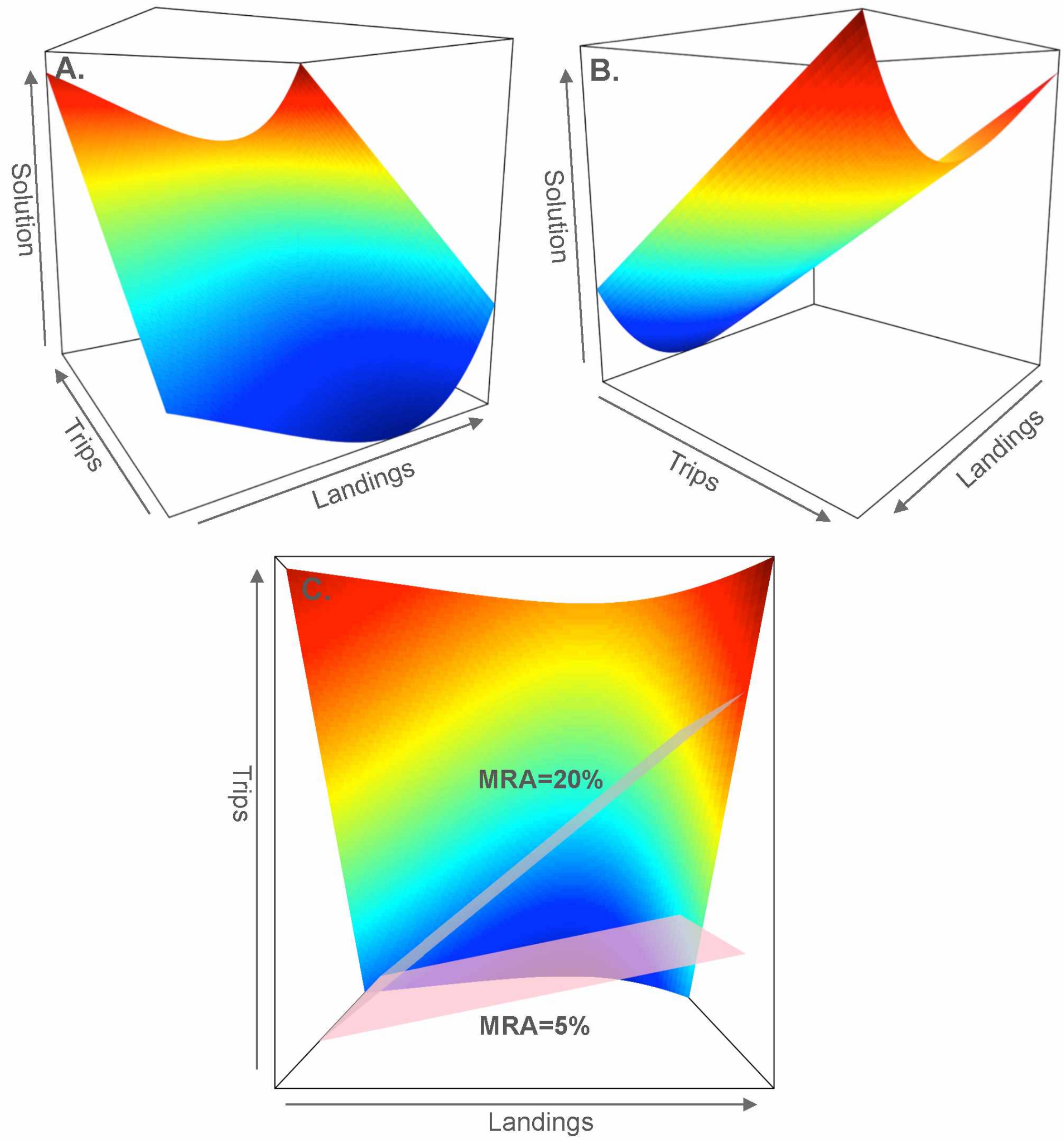


Figure 3.3. Surface plot of the loss function from three angles showing the relationship between landings, trips and the solution of the objective function. Warm and cool colors signify a high and low solution of the objective function, respectively. The polygons in (C) show the maximum retainable amount (MRA) constraints of 5% and 20%. The objective function is constrained to stay above these MRA values.

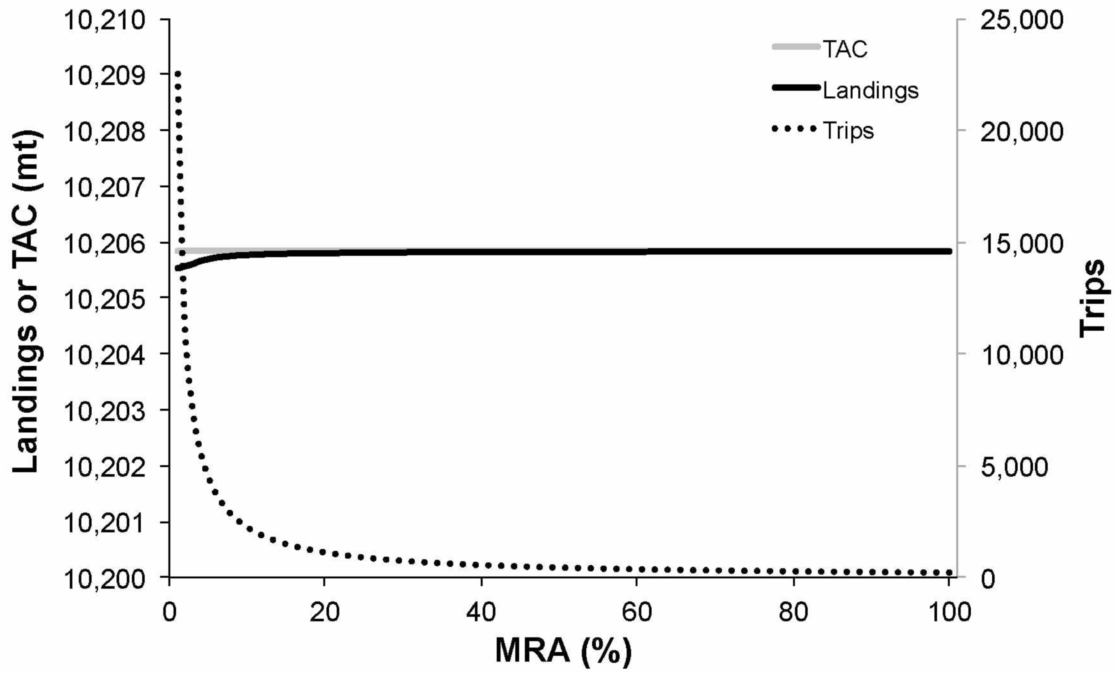


Figure 3.4. Expected amount of landings and trips across maximum retainable amounts (MRA) assuming no discards. Landings are shown on the primary y-axis and represented by the black line). The number of fishing trips is shown on the secondary y-axis and is represented by the dotted line. The total allowable catch (TAC) established by management is represented by the grey line.

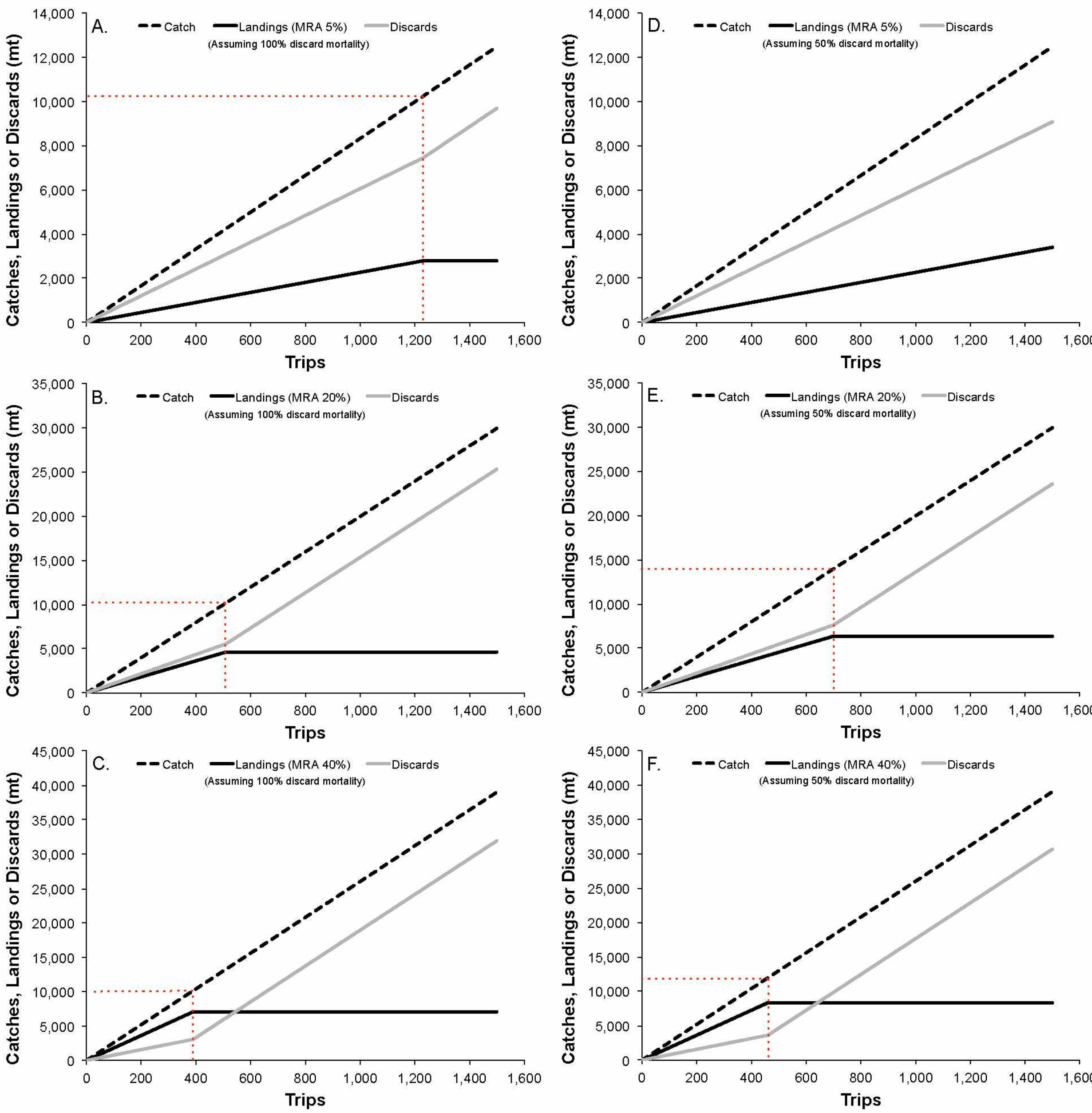


Figure 3.5. Accumulation of skate catches, landings and discards over the course of simulated fishing seasons. Skate catches are represented by the dashed lines, landings by the solid lines, and discards by the grey lines. Fishing seasons are simulated at maximum retainable amounts (MRAs) of 5% (A, D), 20% (B, E) and 40% (C, F), assuming 100% discard mortality (A, B, C) or 50% discard mortality (D, E, F). The red dotted lines represent the number of trips it takes for the catch to reach the total allowable catch (TAC), at which point retention is prohibited, and all skates are discarded.

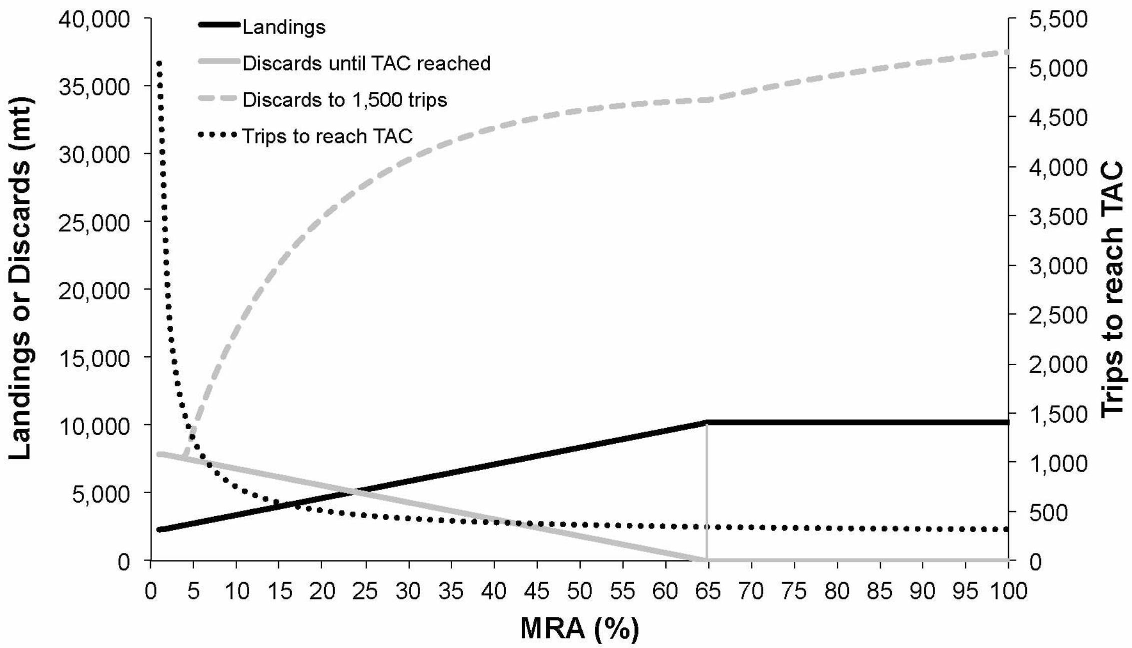


Figure 3.6. Cumulative end of season landings, discards and trips needed to reach the total allowable catch (TAC) across values of maximum retainable amount (MRA). Landings are represented by the solid line, discards by the grey lines, and trips by the dotted line. The solid grey line represents the total amount of discards up until the TAC is reached, and assumes that fishing behavior would change so that no skates were caught after that point. The dashed grey line assumes that fishing behavior does not change after the TAC is reached, and all skates are then discarded. The red vertical line represents the MRA at which there would be no discards until TAC is reached.

General Conclusions

The research presented in this dissertation has advanced our knowledge of skates and skate fisheries in the Gulf of Alaska (GOA). In the first chapter, satellite tagging showed that big skates can undertake long, basin-scale movements, and occupy deeper depths more often than previously assumed. This novel ecological information was accompanied by verification of other assumptions about the wide thermal tolerance of skates, and their use of areas previously identified as skate hotspots in the GOA. Movement patterns and habitat use data can now be integrated into future research and management decisions. For example, the long-range movement potential of big skates provides support for the assumption of a mixed skate stock throughout the GOA, which helps to structure a formal stock assessment.

Using information developed in Chapter 1, the second chapter of this dissertation developed the first stock assessment models for big and longnose skates in the GOA. An age-structured population dynamics model was developed using Stock Synthesis 3 for big and longnose skates separately, which represented an important improvement in modeling these stocks and provides fisheries management the data needed to potentially upgrade these two species from Tier 5 to Tier 3 harvest control rules, under the federal GOA groundfish fishery management plan (FMP). This change in tiers would increase the confidence with which the total allowable catch (TAC) is set for these two skate species overall in the GOA. These models yielded a biomass estimate comparable to what is currently assumed for big skates, but indicated a substantial increase in biomass for longnose skates compared to current management assumptions. However, for both species, the sustainable harvest estimated by the Stock Synthesis models was similar to the current allowable biological catch (ABC) used by management. This suggests that even if the new model is accepted for stock assessment purposes, it is unlikely that the TAC for either species will be increased in the near future.

Given the model-estimated values of sustainable harvest of these two skate species, the third chapter of this dissertation dealt with the profitability of different biologically-sustainable skate harvest strategies. A bioeconomic simulation-optimization model was used to explore the effect of changes in either the skate TAC or maximum retainable amount (MRA) of all skate species combined. Results suggest that under current prices of both target and bycatch species, and given the multispecies character of the GOA groundfish fishery, harvesters are likely to continue to land as much skate as permitted. In addition, the model confirmed that under current market conditions and management measures, decreases in the skate MRA would lead to increases in the number of trips that land skates, but not to a decrease in total skate landings. Decreasing the skate MRA may therefore increase fishing mortality caused by increased skate discards.

Our Chapter 3 findings have repercussions on the profitability and sustainability of the skate fishery. With a lower MRA, more fishermen may be able to derive shares of the revenue generated from skates, as the allowable catch is not at risk of being concentrated in space and time through a race-for-skates. However, lowering the MRA is unlikely to affect total landings; and, if skate discards are underreported or underestimated, a reduced MRA risks increasing fishing mortality (from combined landings and discards) to levels above the TAC. While accurate accounting of discards and discard mortality could prevent ecological losses due to exceeding the TAC, imposition of restrictive MRAs may shift the

TAC from landings to discards and thereby decrease total landings and exvessel and wholesale revenues from skate fishing. That is, overly restrictive MRAs are economically wasteful and violate the National Standard 1 of the Magnuson-Stevens Fisheries Conservation and Management Act by preventing achievement of optimum yield. These considerations must be taken into account when making fishery management decisions. While it may not be possible to increase the net revenue generated from skates by increasing skate landings through increases in the TAC, it is entirely possible to squander the value of this fishery through management measures, such as restrictive MRAs, that divert catch from landings to discards. Instead, it behooves the North Pacific Fishery Management Council (NPFMC) to examine proven management strategies, such as individual or cooperative catch shares or deemed values (i.e. a form of Pigouvian tax) that reduce discards, reduce economic and ecological costs, and preserve revenues and resources.

Currently, skates caught in the GOA are processed very simply. The large pectoral fins, or "wings", are the only products taken from skates for human consumption. These are either removed at sea by catchers/processors, or the whole skate is landed and winged at a shore-based plant. Wings represent about 30% of the average round weight of skates; and in general, the remainder of the skate carcass is discarded or added to the stream of carcasses rendered to fishmeal. Skate wings from Alaska are flash frozen, packed, and with no further processing, exported to Asian countries, primarily Korea. It is my opinion that the easiest way to increase the value of the skate fishery in the GOA is to produce more value-added product, develop co-products (e.g., chondroitin, fish liver oil), and develop local and domestic markets for skate wings.

A side project of this dissertation provided an analysis of the nutritional content and heavy metal load of skate muscle and liver tissues (Appendix B). This analysis found that the meat of big and longnose skates delivered to Cordova and Kodiak, Alaska are composed of lean protein that is low in fat, but with high percentages of polyunsaturated fatty acids. Although some heavy metals are present in skate muscle tissues, these levels were rarely above the EPA screening values and are, on average, similar to levels found in Pacific halibut (*Hippoglossus stenolepis*), a highly-valued fish. Based on human health considerations, this suggests that Alaska-origin skate meat is likely to continue to be in demand in the future and could attract a market in the U.S. In addition, skate livers are very high in lipids, with very favorable fatty acid profiles that include high levels of omega-3 and omega-6 fatty acids. Therefore, the creation of novel, human health targeted products (such as skate liver oil supplements) from GOA skates should be feasible. In fact, such a product has very recently been developed from skates on the U.S. east coast.

My research adds to the greater understanding of two commercially valuable, but biologically vulnerable, skate species. Results from this applied research are directly applicable to the management of skate fisheries in the GOA. For instance, if the stock assessment models are adopted by the NPFMC, they will provide a basis to estimate overfishing limits and acceptable biological catches for these species. Incorporation of best available science regarding skate ecology, population dynamics, and fishery bioeconomics into management fosters responsible development of skate fisheries, sustainable fishery revenues and employment, and a reduced risk of the overfishing, stock collapse, and prolonged fishery closures that typify skate fisheries elsewhere in the world.

Appendices

Appendix A

Supplementary Material for Chapter 2

First stock assessment models for big (*Beringraja binoculata*) and longnose (*Raja rhina*) skates in the Gulf of Alaska: Development of a Stock Synthesis model.

Table A-1. Parameters and data sources used in the SS3 model.

Parameter	Starting value in model	Source
Natural mortality	0.1*	Ormseth 2015
First age at maturity (yr)	10*	Gburski et al. 2007; Ebert et al. 2008
Min length (cm)	30*	Gburski et al. 2007
Max length (cm)	247.5*	Gburski et al. 2007
Von Bert K	0.08*	Gburski et al. 2007
Weight-length scale	$5x10^{-6}$	Farrugia unpublished data
Weight-length exponent	3.1064	Farrugia unpublished data
Maturity curve inflection	148.6	Ebert et al. 2008
Maturity curve slope	-0.548	Ebert et al. 2008
Beverton-Holt R0	10*	Gertseva 2007 (US west coast longnose stock assessment)
Beverton-Holt steepness	0.21*	Gertseva 2007 (US west coast longnose stock assessment)
Stock-recruitment sigmaR	0.3	Gertseva 2007 (US west coast longnose stock assessment)
Catchability	1	Ormseth 2016 (BSAI Alaska skate stock assessment)

* These parameter values were allowed to be estimated within the model.

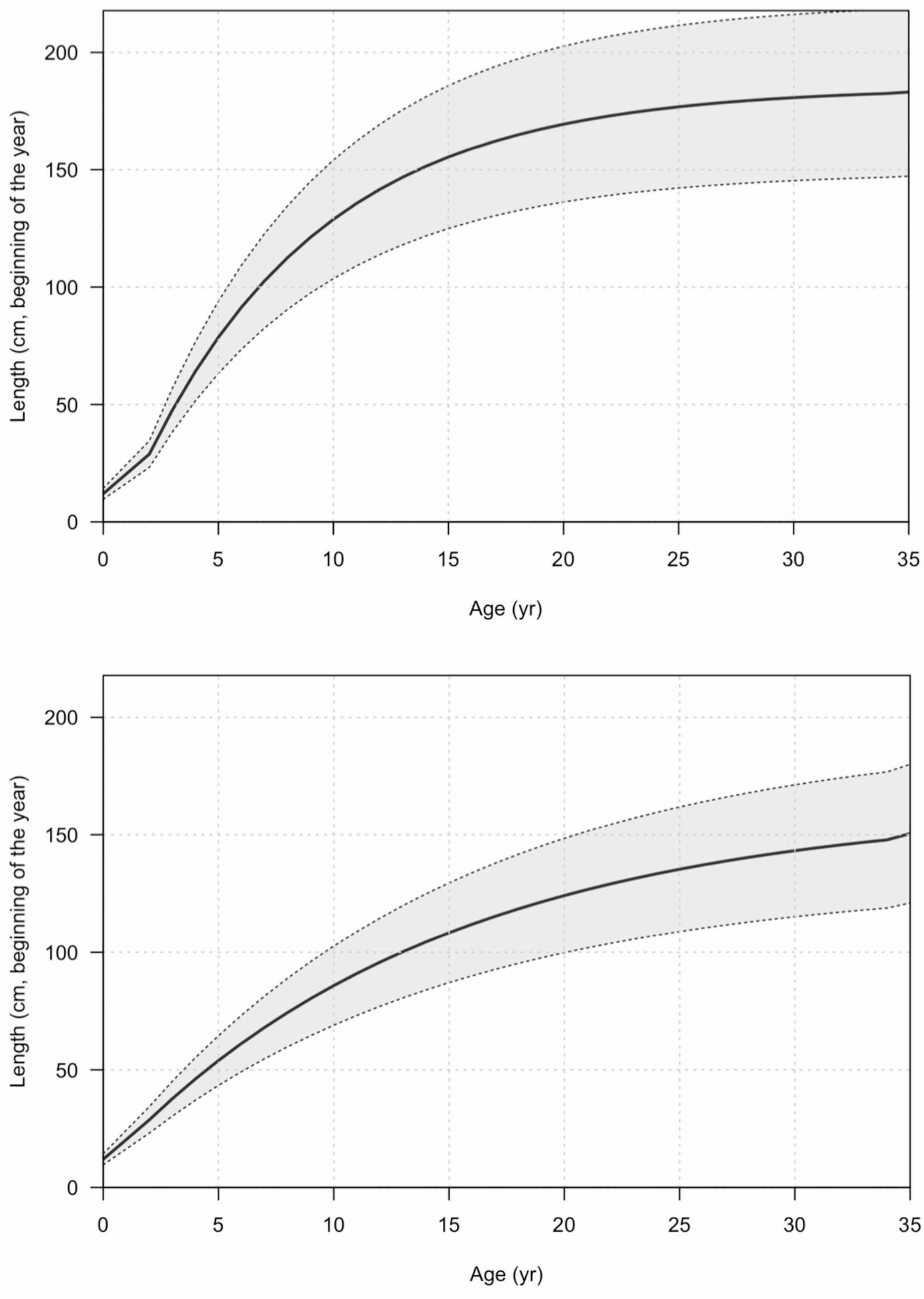


Figure A-1. Length at age for skates in the beginning of the season in the ending year of the model. Big skates are shown in the top panel, longnose skates in the bottom panel. Shaded area indicates 95% confidence intervals of length at age around estimated growth curve. The age 35 category is a 'plus' group, containing all ages of 35 years and above.

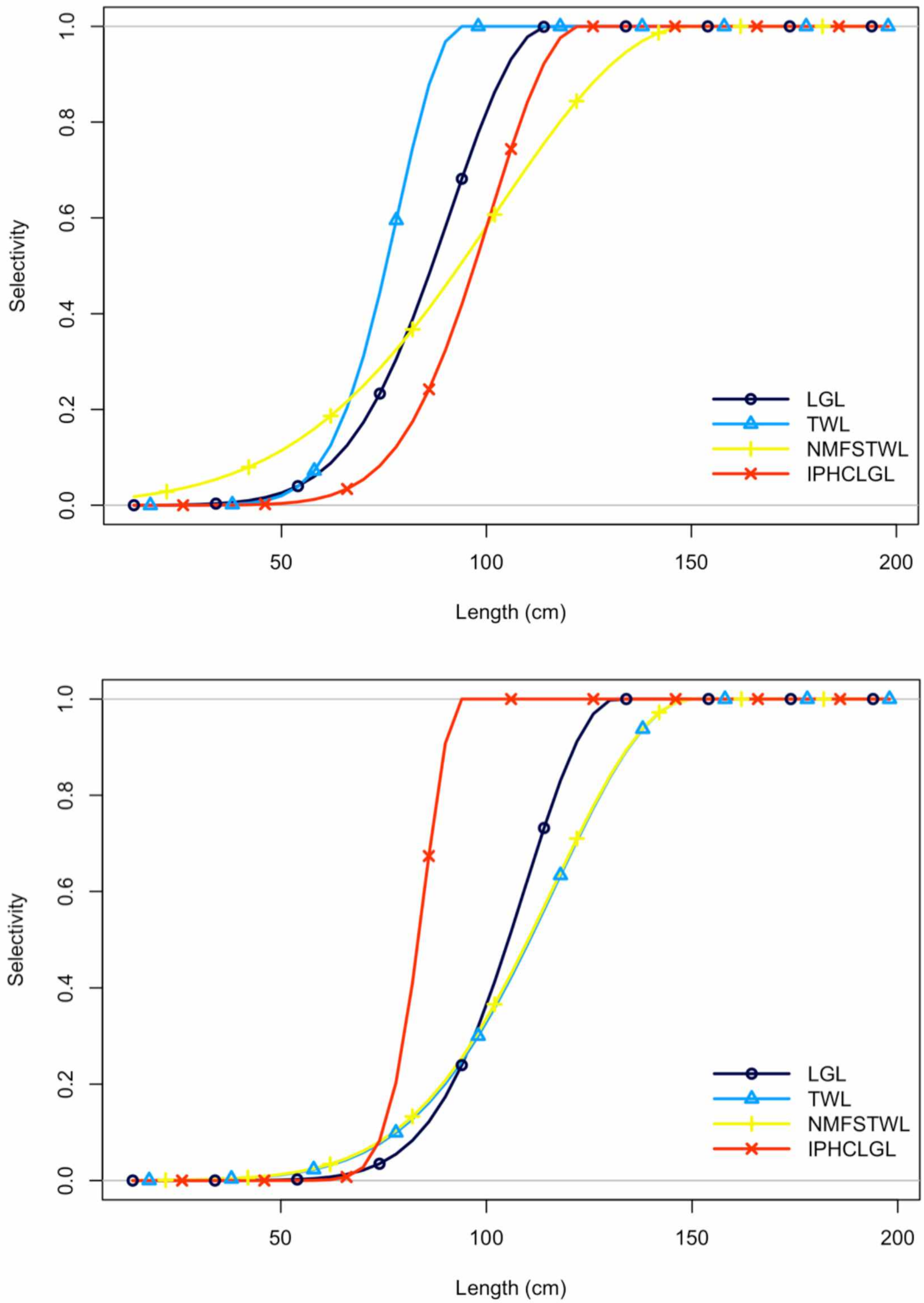


Figure A-2. Selectivity at length for all four fleets for skates. Big skates are shown in the top panel, and longnose skates in the bottom panel. Fleets are divided by commercial longline (LGL), commercial trawl (TWL), trawl survey (NMFSTWL) and longline survey (IPHCLGL).

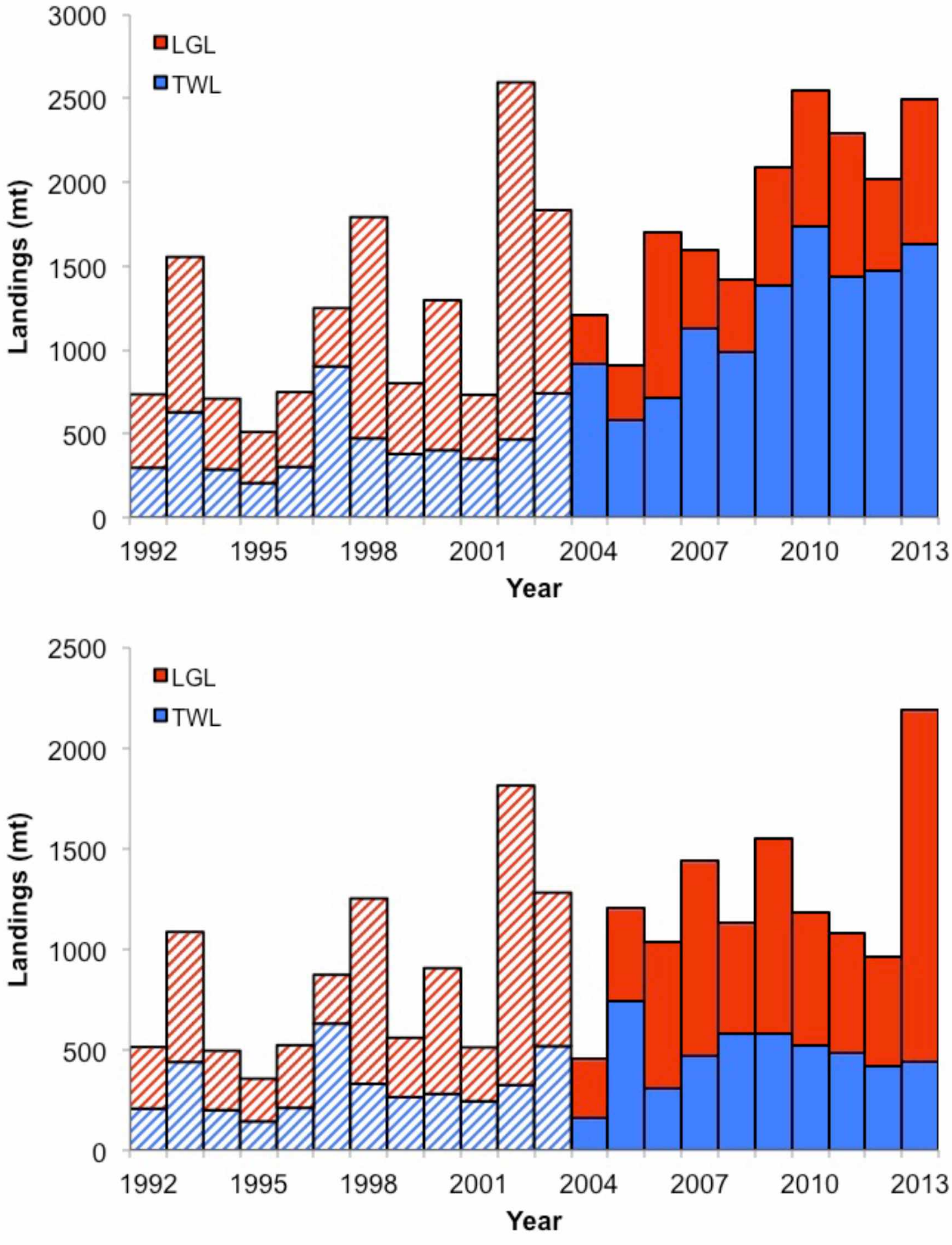


Figure A-3. Landings of skates in the Gulf of Alaska in longline and trawl fisheries. Landings are shown for big skates (top) and longnose skates (bottom) from longline (LGL – blue) and trawl (TWL – red) fleets. Hashed bars represent years for which the species-specific landings were apportioned based on later catch compositions (see Chapter 2 methods).

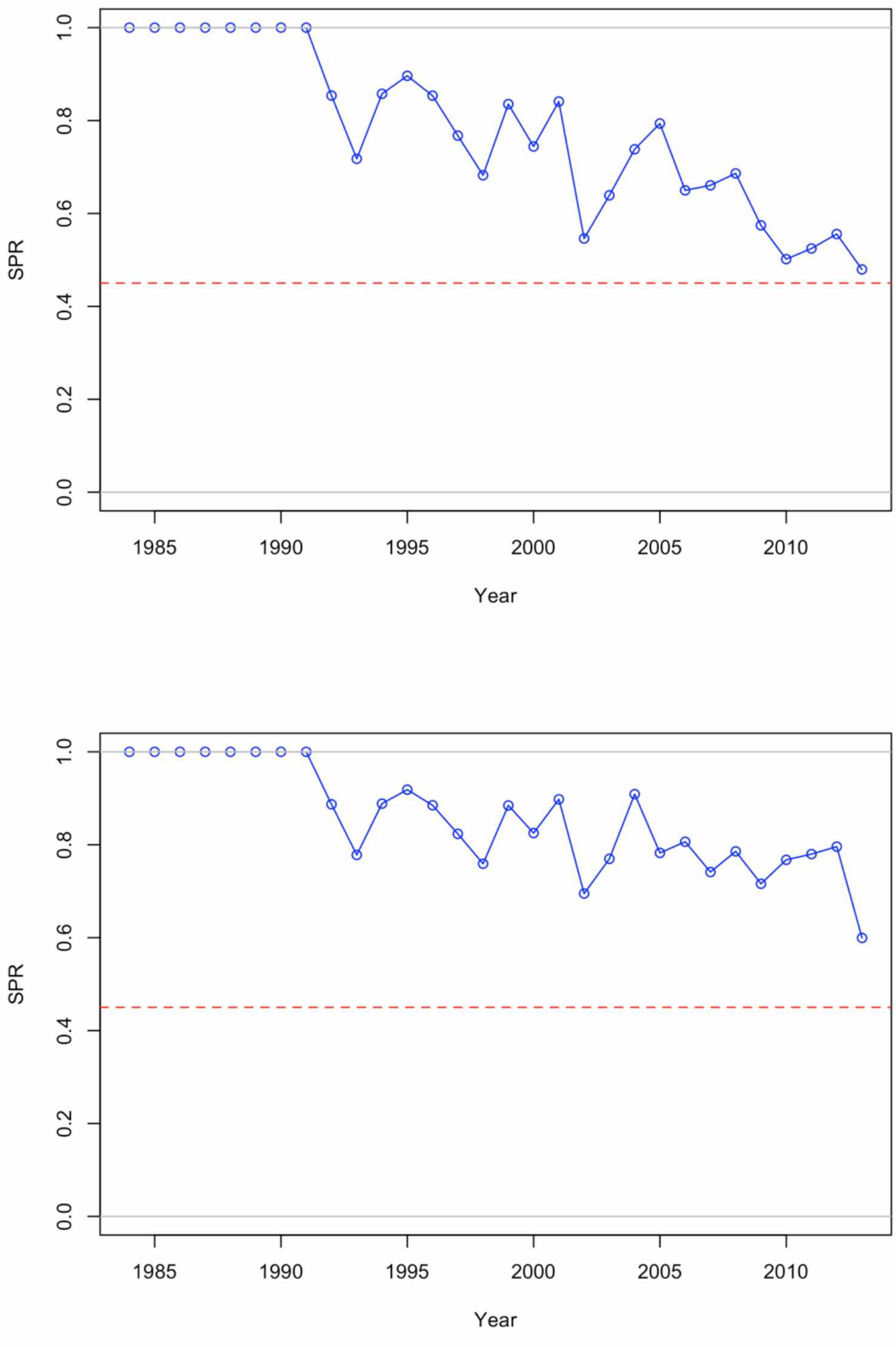


Figure A-4. Time series of the spawning potential ratio (SPR) for skates. Big skate SPR is shown in the top panel and longnose skates in the bottom panel, with management target (red dashed line) set at 45% of unfished SPR.

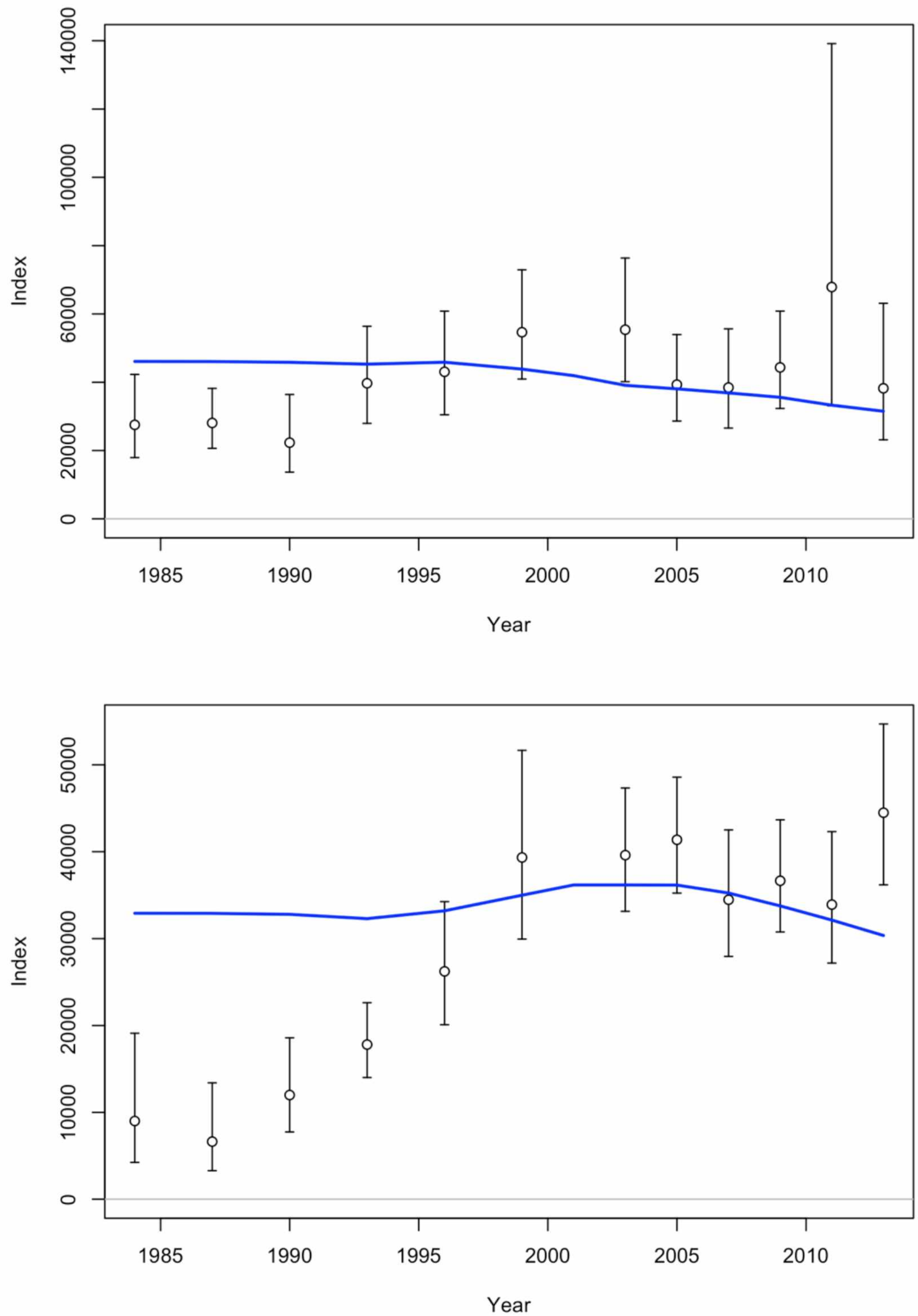


Figure A-5. Model fit to the trawl survey index. Big skates are shown in the top panel and longnose skates in the bottom panel. Lines indicate 95% confidence intervals around index values.

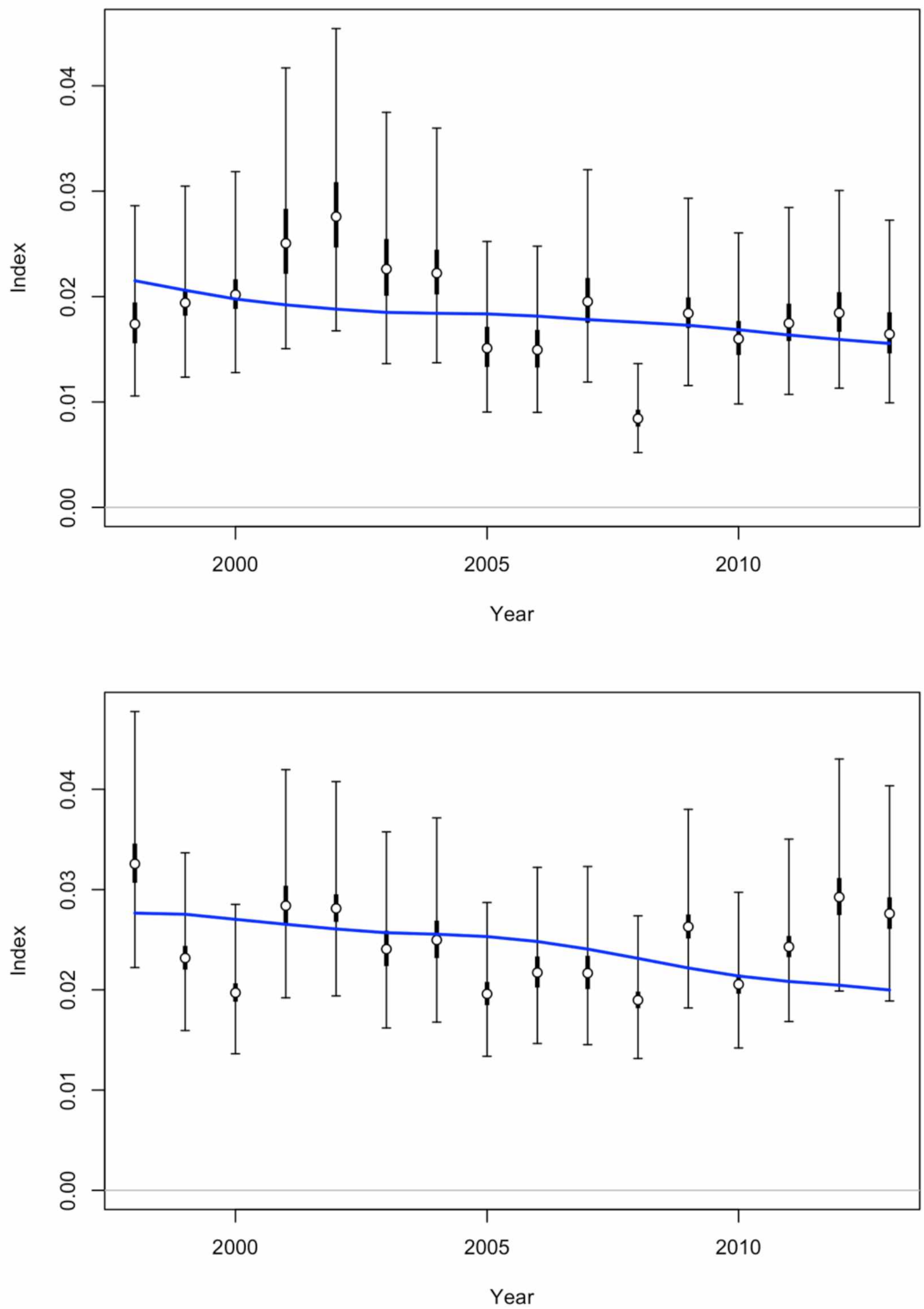


Figure A-6. Model fit to the longline survey index. Big skates are shown in the top panel and longnose skates in the bottom panel. Lines indicate 95% confidence intervals around index values. Thicker lines indicate input uncertainty before addition of estimated additional uncertainty parameter.

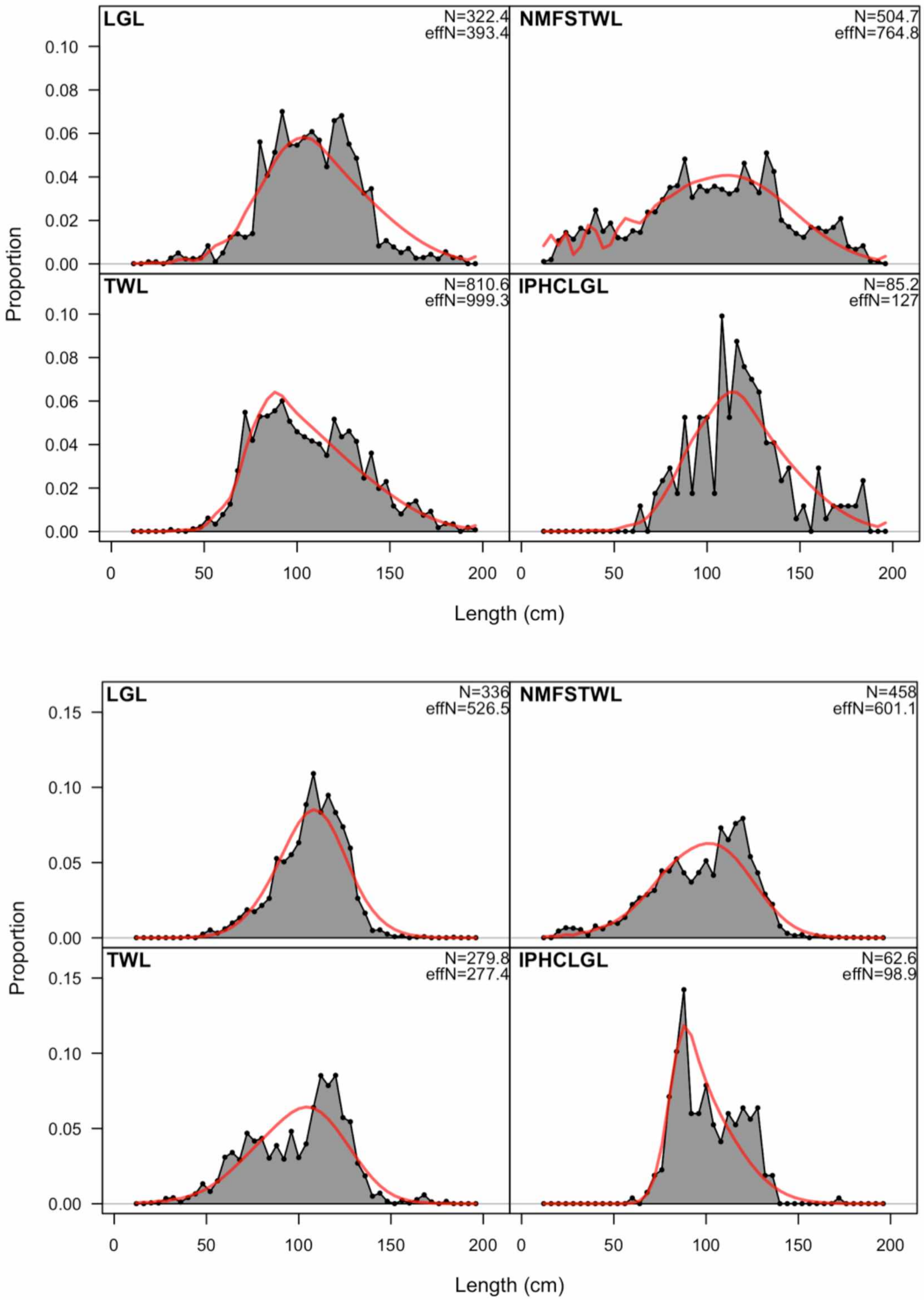


Figure A-7. Length compositions for skates in the surveys and fisheries. Raw data (grey) and model estimates (red) are shown for big skates (top) and longnose skates (bottom) for the commercial longline fleet (LGL), commercial trawl fleet (TWL), trawl survey (NMFSTWL) and longline survey (IPHCLGL). Sample sizes and effective sample sizes are specified in the corner of each panel.

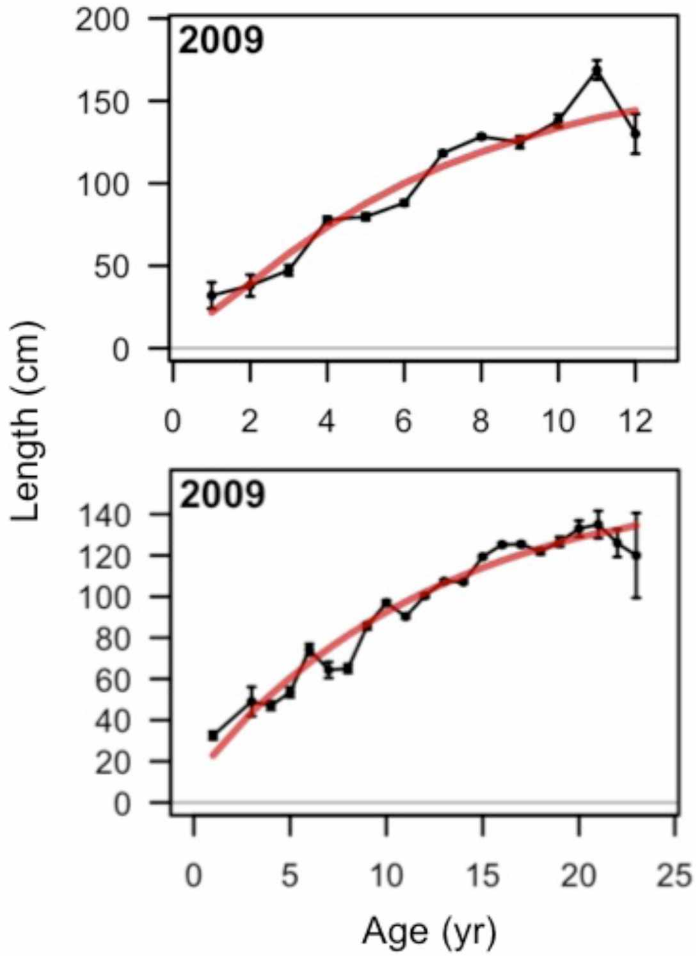
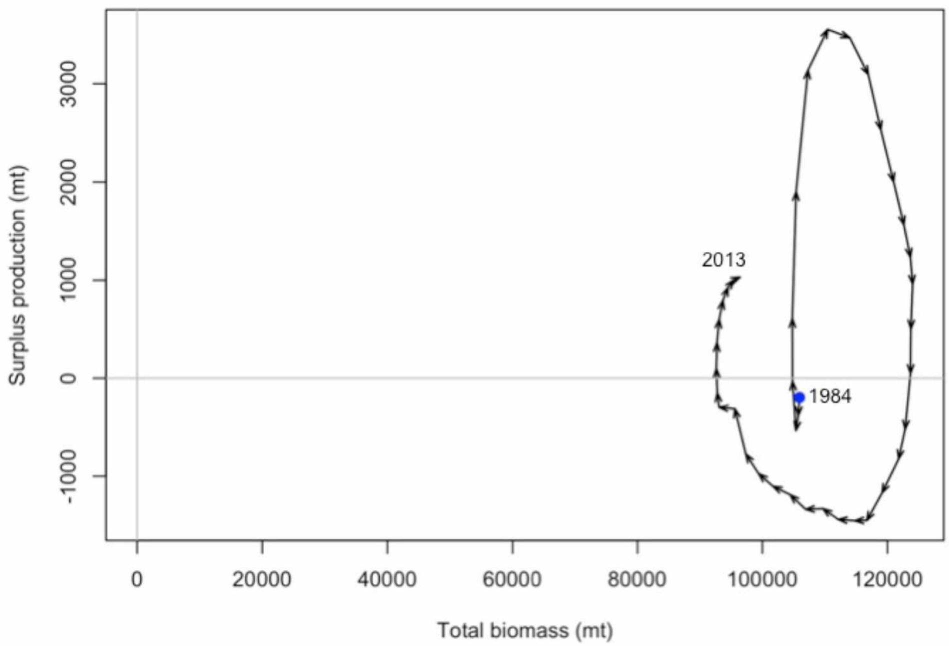


Figure A-8. Mean length at age for skates. Data for the year when ageing data was available (2009) is shown in black and model estimates in red, for big skates (top) and longnose skates (bottom).



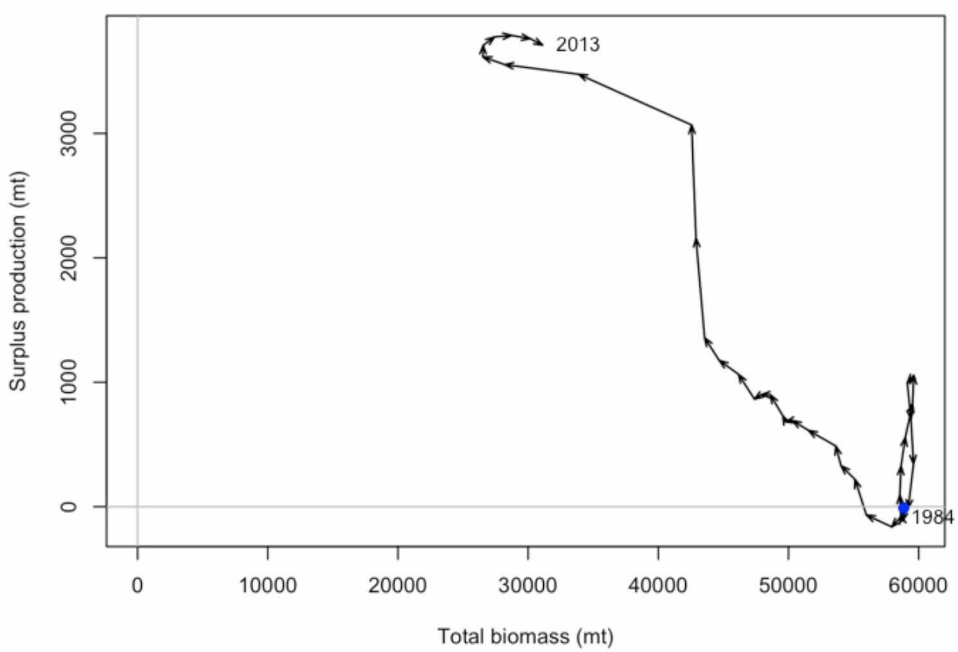
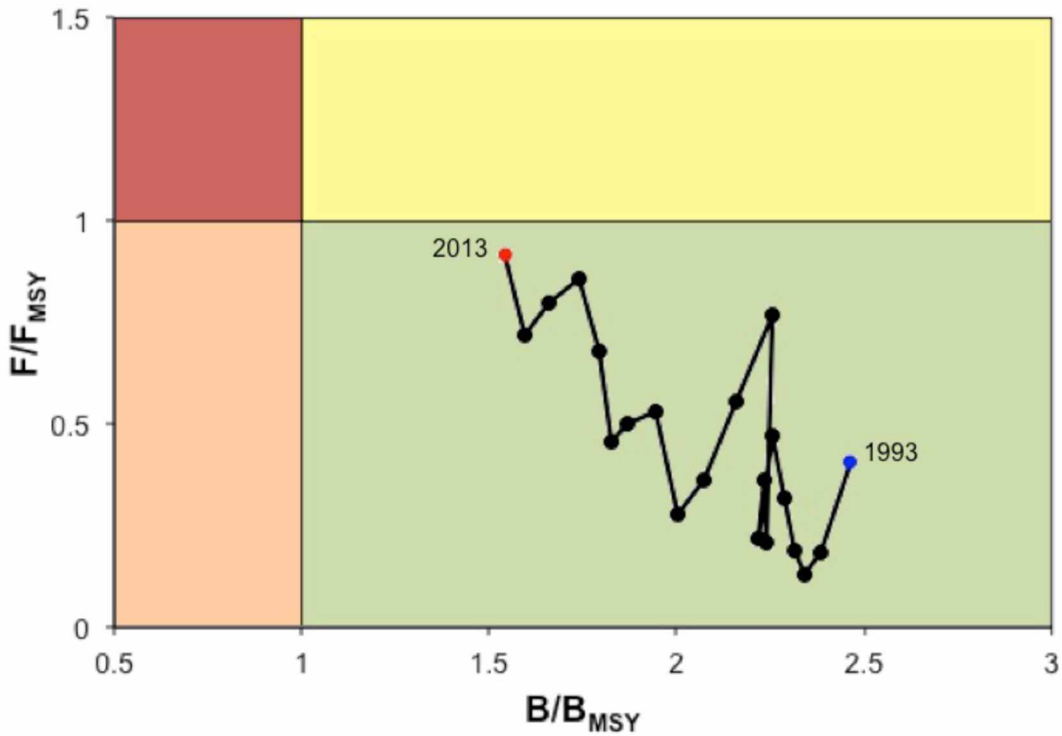


Figure A-9. Surplus production plots for skates between 1984 and 2013. Big skates are shown in the top panel and longnose skates in the bottom panel. Arrows indicate the time progression.



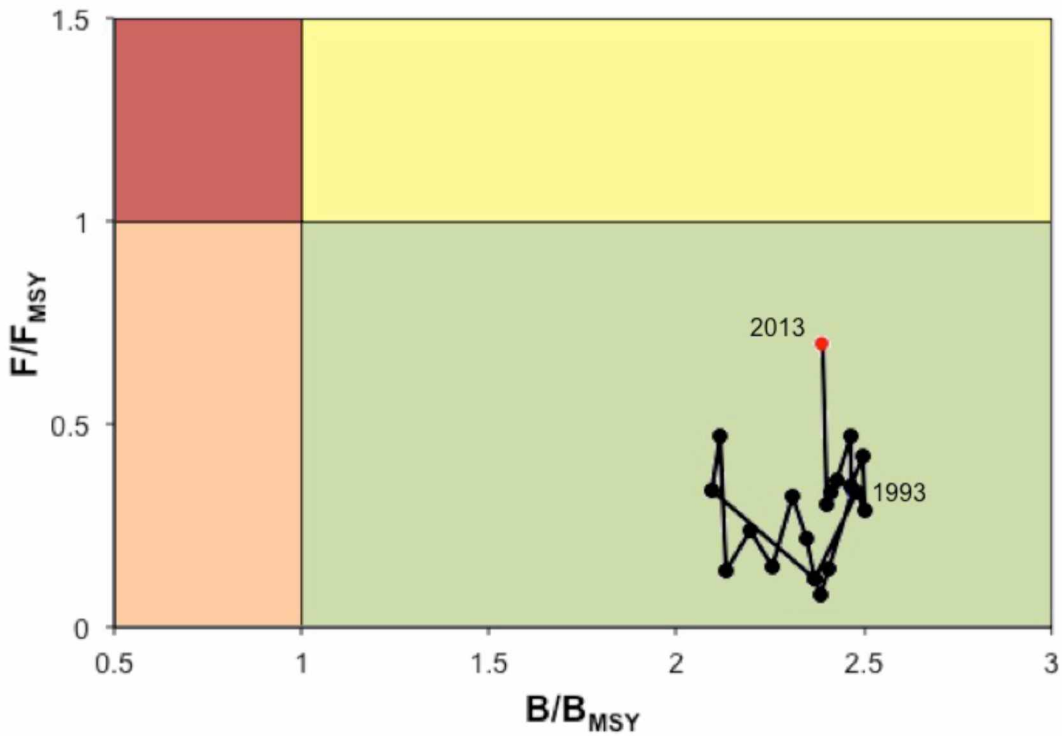


Figure A-10. Kobe plots for skates in the Gulf of Alaska. The historical ratios of F/F_{MSY} versus biomass relative to B_{MSY} are shown for big skates (top) and longnose skates (bottom). Start (blue) and end years (red) are labeled.

Appendix B

Nutritional Content, Mercury, and Trace Element Analyses of Two Skate (Rajidae) Species in the Gulf of Alaska[5]

B.1 Abstract

Seafood is recognized as an important source of proteins and long chain omega-3 fatty acids. However, one of the primary concerns with seafood consumption is the level of heavy metals, particularly mercury, present in fish tissues, which may influence the demand of certain fishery products. We sampled muscle and liver tissues from 20 big (*Beringraja binoculata*) and 20 longnose (*Raja rhina*) skates collected near Kodiak and Cordova, Alaska, and analyzed their nutritional content (protein, moisture and lipid content and fatty acid profiles), heavy metal (mercury, arsenic, cadmium, lead) and trace element (selenium) load. Big and longnose skate muscle was composed of lean protein (14.7% ± 0.7% SD) with 1.2% (± 0.4%) lipids and 83% (± 0.8%) moisture. Skate livers were very high in lipids, between 52.5 and 57.5% and had high percentages of omega-3 fatty acids (30.2%). Mercury in these skates had mean levels of 0.21 mg/kg, lower than average levels found in Pacific halibut (*Hippoglossus stenolepis*). Overall, the risk/benefit ratio of consuming skate muscle was slightly positive (3.62%) based on the balance of mercury toxicity and omega-3 fatty acid benefits. Big skates were overall more beneficial to consume, and only longnose skates from Cordova had a negative risk/benefit ratio. These data can be used by the fishing industry to understand current and future market demands

[5] Farrugia, T.J., Oliveira, A.C.M., Knue, J.F., Seitz, A.C. 2015. Journal of Food Composition and Analysis 42:152-163, doi: 10.1016/j.jfca.2015.03.013.

for skate products, and to be aware of any health concerns of consuming Gulf of Alaska skates.

B.2 Introduction

Seafood is an important source of lean high quality protein, amino acids, polyunsaturated fatty acids (PUFA), vitamin D and iodine (Sioen et al. 2009), providing many health benefits to consumers (WHO 2003). Fatty acids are important for normal growth and metabolism and essential to cell membrane function. In particular, they help maintain healthy neurological and cardiovascular systems, and have a positive effect on neurological development, especially cognitive and ocular functions (Racine and Deckelbaum 2007). Fish liver oils are an excellent source of omega-3 and omega-6 PUFAs, specifically the omega-3 long-chain fatty acids eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). Both EPA and DHA have proven cardiovascular, inflammatory and neurological benefits (Racine and Deckelbaum 2007), and dietary supplements made from fish liver oils are popular products.

However, one of the primary concerns of consuming fish and shellfish is the level of contaminants present, such as heavy metals like arsenic, mercury, cadmium, copper, and lead (Ginsberg and Toal 2009). Selenium is an essential nutrient that binds and sequesters most other heavy metals to reduce their toxicity but has deleterious effects at high doses (US EPA 2009). In particular, recent studies have shown that selenium may offset the effects of methylmercury toxicity (Ralston and Raymond 2010). Kaneko and Ralston (2007) even suggested that seafood consumption advisories should use the mercury to selenium ratio rather simply mercury concentration when assessing risks of seafood consumption.

Mercury and arsenic can both be found in either an organic or inorganic form in seafood (IOM 2006). The organic form of arsenic (e.g., when it is combined with carbon and hydrogen as in arsenobetaine, a compound found in fish and shellfish) is considered non-toxic (ATSDR 2007). However, inorganic arsenic (e.g., when combined with oxygen, chlorine or sulfur) can have toxic effects on gastrointestinal, cardiovascular and central nervous systems and lead to death (US EPA 2009). Conversely for mercury, inorganic mercury is not considered deleterious whereas the organic form, methylmercury, has been linked to cardiovascular, developmental, and neurological defects (IOM 2006). The US Food and Drug Administration (FDA) and US Environmental Protection Agency (US EPA) have issued advisories recommending that young children and pregnant and nursing mothers avoid consuming certain types of fish thought to be high in methylmercury (e.g., sharks, swordfish *Xiphias gladius*, tilefish *Lopholatilus chamaeleonticeps*). In addition, awareness of the toxic effects associated with mercury toxicity in fishes is increasing in the U.S. and could influence the demand of certain fishery products (Lando and Zhang 2011). This tradeoff between risks and benefits of consuming seafood can make it difficult to provide clear fish consumption advice to the public, necessitating quantitative approaches that analyze these tradeoffs and develop species-specific guidelines (Ginsberg and Toal 2009).

Despite the uncertain risk/benefit tradeoff, demand for fishery products is increasing worldwide while wild-caught landings remain stable (FAO 2014). To meet the demand, aquaculture (fish farming) is increasing, but fisheries will also likely increasingly target underexploited stocks. Specifically, there will be escalating economic pressures to maximize local landings of underexploited stocks of species that are in high demand globally or that are overexploited in other areas. In addition, fishing communities experiencing decreased catch rates of traditional species (e.g., salmon *Oncorhynchus* spp., Pacific halibut *Hippoglossus stenolepis*, Pacific cod *Gadus macrocephalus*) may need to diversify their catch to include underexploited stocks to remain economically resilient. Alaska is the largest producer of seafood in the United States (NMFS 2012), and several underexploited fishery stocks, including the giant Pacific octopus (*Enteroctopus dofleini*), arrowtooth flounder (*Atheresthes stomias*) and skates (family Rajidae), are being considered as fishery targets for increased harvest (ADCCED 2009).

Skates (family Rajidae) are dorsoventrally compressed cartilaginous fishes related to sharks and rays, and are fished for their pectoral fins or "wings." Skate stocks off Alaska are not overfished, nor subject to overfishing (NOAA 2005; NMFS 2013). As such, the Alaska Department of Commerce, Community and Economic Development encourages the development of skate fisheries in Alaska in the future (ADCCED 2009) and seafood exporters are interested in buying skates from Alaska for sale in Asia (Dr. Quentin Fong, Seafood Marketing Specialist, Kodiak Seafood and Marine Science Center, pers. comm.). However, the economic sustainability of a skate fishery is dependent on the continued future demand for skates, which in turn will reflect the risks and benefits of consuming skates from Alaska. Therefore, the benefits and risks of skate products from Alaska should be studied before changes in the fishing industry and management are undertaken to increase skate catches.

Of the 15 species of skates common to Alaskan waters, the big (*Beringraja binoculata*, formerly in the *Raja* genus; Ishihara et al. 2012) and longnose skates (*Raja rhina*) grow the largest (Eschmeyer et al. 1983) and are the most commonly captured species in the Gulf of Alaska (GOA) (Ormseth and Matta 2011). Because these two species are considered underexploited (ADCCED 2009) the fishing industry is interested in expanding skate landings. Despite this demand for increased skate harvest, there is little information on the nutritional value and contaminant load of big and longnose skates, which could be critical to understand the long-term demand for skate products from GOA. In addition, only the wings are currently retained, with 65 to 70% of the weight of the skate being discarded leading to a potential loss of revenue. Additional products that could be recovered from GOA skates are cheeks, which are relatively large in the big skate, fish oil from livers, and low-ash fishmeal from the remainder byproducts, all of which represent additional sources of revenue that currently are not realized.

Therefore, both the current skate product (wing muscle) and a potential product (liver) should be evaluated for nutritional content and contaminant load as part of the proposed development of the big and longnose skate fishery in GOA. These data may give us insight into the future demand of skate products and help us maximize the revenue of the skate fishery without increasing the skate harvest to potentially unsustainable levels that would lead to overfishing. In this study, we performed nutritional content and trace metal analyses of the wing muscles and livers of big and longnose skates from Kodiak and Cordova, Alaska, and determined the risk/benefit ratio of consuming these skates. Previous research on longnose skates showed that their livers contained very high lipid content (Wu et al. 2011), as did livers of most shark species (Navarro-Garcia et al. 2000), which led us to hypothesize that our samples would also show high lipid content in livers, and conversely lean protein in the muscle samples. We further hypothesized that big and longnose skate tissues would show high levels of heavy metals, similar to other elasmobranch species (Endo et al. 2008; Hurtado-Banda et al. 2012).

B.3 Materials and Methods

B.3.1 Sampling locations and procedures

Big and longnose skates were collected from longline or trawl fishing boats during their offload to processing plants in Kodiak and Cordova, Alaska. Skates sampled in Kodiak were caught in the federal statistical areas 525630 and 545602, south of Kodiak Island, whereas the Cordova samples were caught in Prince William Sound, statistical area 476031 (Figure B-1). Ten individuals of each species (Figure B-2) were collected at each port for a total sample size of 40 skates. Big skates were sampled in Kodiak in October 2012, while big skates from Cordova and longnose skates from Kodiak and Cordova were sampled in April 2013. Each skate was sexed, measured – total length and disc width (width from pectoral fin tip to fin tip) to the nearest 1 cm – and weighed to the nearest 0.01 kg.

The whole liver and both pectoral fins (wings) were sampled from each individual, weighed, vacuum packed and placed in a -40°C blast-freezer for storage. Subsamples of each tissue type from each individual were taken for analysis. Each subsample consisted of three pieces of ~10 g of each tissue taken throughout the wing muscle or liver and homogenized together. The muscle subsamples were taken from the wing while still frozen at three locations along the thickest part of the wing (Figure B-2B). Care was taken to not include cartilage or skin tissue in the muscle samples. Muscle subsamples were then weighed, lyophilized using a freeze-drier model Genesis 65S (VirTis SP Scientific, Warminster, PA, USA), ground with a pestle and mortar, vacuum-packed and returned to the blast freezer until analysis. Livers were subsampled while frozen by taking a small piece of tissue from the center of each of the three lobes of the liver, taking care not to sample large blood vessels (Figure B-2C). Each subsample was vacuum-packed, labeled and returned to the blast freezer until analysis. The workspace as well as all tools were cleaned with ethanol and allowed to air dry between samples to avoid cross-contamination.

B.3.2 Proximate composition analysis

A proximate composition analysis of the liver and muscle subsamples was carried out for each of the 40 individuals. First, the moisture, inorganic ash, protein and lipid contents of each sample were determined, after which the fatty acids were converted to fatty acid methyl esters (FAME) and quantified to determine the fatty acid profile.

B.3.2.1 Moisture and ash

The moisture content of the freeze-dried muscle and wet liver samples was determined by placing 0.5 g of each sample in a 105°C oven for 24 hours (method 952.08, AOAC 2005). The moisture content was then determined by subtracting the dried sample from the initial weight of the sample (before freeze drying in the case of muscle). The dried samples were then placed in a muffle furnace (Lindberg Blue M, Thermo Scientific Inc., Asheville, NC, USA) set at 550°C for 24 hours, and the remaining ash was weighed (method 938.08, AOAC 2005).

B.3.2.2 Protein

Freeze-dried muscle samples were powdered and approximately 0.1 g of each sample was placed in a nitrogen analyzer model FP-528 (LECO Corporation, St Joseph, MI, USA), which measured total nitrogen content in percent weight (following method 968.06, AOAC 2005). The level of detection (LOD) of the nitrogen analyzer was determined by calculating the standard deviation of standards that were run before muscle samples and every eight to ten samples. The LOD was found to be 0.02% based on 18 readings of the standard. The total nitrogen value was then multiplied by 6.25 to estimate the total protein content of each sample as a percentage of the total sample weight (FAO 2003; AOAC 2005). Liver samples could not be freeze-dried and the protein content was not directly measured. Instead, the protein content of liver samples was estimated by subtracting the lipid, moisture and ash percentage from 100%.

B.3.2.3 Lipid

Lipids were extracted from the freeze-dried muscle and wet liver samples differently. Freeze-dried muscle samples were ground and 0.5 g of each sample was placed in an accelerated solvent extraction system (ASE200, Dionex, Sunnyvale, CA, USA) as in Bechtel et al. (2010). The freeze-dried muscle tissue was ground with a mortar and pestle, mixed with the Chem-Tube Hydromatrix (Varian Inc., Palo Alto, CA, USA) and placed in the 40-mL ASE cells. HPLC-grade dichloromethane was used to extract the lipids at 80°C under pressurized nitrogen (10.34 MPa) with the following 15-minute procedure: 1-minute fill time, 5-minute heating, 5-minute static cycle, 2-minute purge time. The resulting solvent-lipid solution was then placed in a TurboVap LV Evaporator (Caliper Life Sciences, Hopkington, MA, USA) at 45°C and flushed with nitrogen until all the solvent was extracted. The ASE vials were then weighed and the total lipid weight was calculated by subtracting the original vial weight.

The livers were too fatty and could not be effectively freeze-dried, thus the ASE procedure could not be used. Instead, lipids were extracted from the livers using the Folch method (Folch et al. 1957) with slight modifications (Brenner et al. 2012). Briefly, samples of 5 g of liver were homogenized with a 2:1 chloroform-methanol solution with 0.01% butylated hydroxytoluene, flushed with nitrogen gas and refrigerated overnight. The samples were then filtered through a 42 mm Büchner funnel, transferred to a 125 mL separatory funnel along with 18 mL of 0.88% KCl, inverted several times to mix thoroughly and allowed to sit until the phases separated. The lower lipid phase was then retained, mixed with anhydrous sodium sulfate and the solvent was evaporated using a stream of nitrogen gas in the TurboVap LV until a constant weight showed that only lipids remained. For both muscle and liver samples, the weight of the final lipid fraction was measured and used to calculate the percentage of tissue composed of lipids. Lipids were then resuspended in hexane with 0.01% butylated hydroxytoluene and stored in a -80°C freezer.

B.3.2.4 FAMEs

Fatty acid methyl esters (FAMEs) were extracted from the lipids of each muscle and liver sample following the procedure in Maxwell and Marmer (1993), using 10 µl of C23:0 as the internal standard at a 10 mg/mL concentration. FAMEs were analyzed using a gas chromatography system model 6850 coupled to a flame ionization detector and fitted with an auto sampler model 7683 (Agilent Technologies, Wilmington, DE, USA), as previously described by Oliveira et al. (2006). The initial oven temperature was 140°C, increased to 180°C at a rate of 2°C/min then to 200°C at a rate of 0.5°C/min and to 203°C at a rate of 1°C/min. The final oven temperature increase was at a rate of 20°C/min to 220°C to remove all potential sample residues from the column prior to next injection. The total run time was 65 min. The inlet temperature was 250°C and the sample was injected in split mode at a100:1 ratio. Hydrogen was used as the carrier gas at a constant flow mode with an initial flow of 1.0 mL/min and average velocity of 30 cm/sec. The flame ionization detector was operated at 275°C with hydrogen flow of 40 mL/min, airflow of 450 mL/min and nitrogen as makeup gas at 35 mL/min. The capillary column used was a DB-23 (Agilent Technologies Model 19091H-136E; 60 m X 250 micrometers x 0.25 micrometer film thickness). Sample injection volume was 1 µL. A Supelco (Bellefonte, PA) S-37 standard was run prior to samples for identification of peaks. The GC-FID outputs were analyzed using the ChemStation software (Agilent Technologies Inc., Santa Clara, CA, USA).

B.3.3 Trace element and heavy metal analysis

Liver and muscle subsamples were analyzed for contaminant load at the Alaska State Environmental Health Laboratory. Concentrations of total mercury, arsenic, cadmium, copper, lead and selenium were determined for each subsample, and corrected back to wet weight for the freeze-dried muscle samples as described below.

B.3.3.1 Mercury

Total mercury in the subsamples was determined using a DMA-80 (Milestone Inc., Shelton, CT, USA) direct mercury analyzer following US EPA method 7473. Approximately

0.1 g to 0.2 g (± 0.02g) of sample was placed in a quartz boat that was inserted into the decomposition furnace, which thermally and chemically decomposed the samples at 200°C for 1-2 minutes. Flowing oxygen carried the decomposition products to the catalyst furnace, which trapped halogens and nitrogen/sulfur oxides. The remaining products were then carried to a gold amalgamator, which selectively trapped mercury. The system was flushed with oxygen after which the amalgamator was heated to 650°C to release the mercury vapors that were passed through a spectrophotometer that measured absorbance at 253.7 nm and determined mercury content. The method detection limit (MDL) for mercury was 0.0048 mg/kg. To ensure the quality of the mercury results, we analyzed the fish protein DORM-4 certified reference material (CRM) from the National Research Council Canada (NRCC, Ottawa, Canada). For each batch of twenty samples, an instrument blank, matrix spike, and matrix spike duplicate were analyzed along with the samples. The instrument blank acceptance criteria were less than half the method reporting limit.

This method only measured total mercury content and could not differentiate between elemental mercury and organic methylmercury. Studies have estimated that the percentage of mercury that is methylmercury in marine fish tissues is above 95% (Scudder et al. 2009) and above 90% in elasmobranchs (Pethybridge et al. 2010). For this reason, the following analyses will assume that 100% of the total mercury in skates is methylmercury as a conservative estimate of the risk of consuming skates.

B.3.3.2 Arsenic, cadmium, copper, lead and selenium

Skate tissue content of other heavy metals (arsenic, cadmium, copper, lead) and selenium was measured by US EPA method 6020A using an Elan DRC II (PerkinElmer Inc., Waltham, MA, USA) inductively coupled plasma (ICP) mass spectrometer (MS). Using US EPA 3051A, approximately 0.5 g ± 0.2 g of sample was digested in 10 mL of ultrapure nitric acid, diluted, and analyzed by the ICP, which nebulized the sample allowing the aerosol to be transported by argon gas into the plasma torch. The resulting ions were introduced into the MS, which determined their mass-to-charge ratio and quantified the original amount of each element. We only used this method to measure the total amount of each element and did not differentiate between different forms of the elements. The MDL was 0.0077 mg/kg for arsenic, 0.0014 mg/kg for cadmium, 0.05 mg/kg for copper, 0.01 mg/kg for lead and 0.01 mg/kg for selenium.

To ensure the quality of the measurements, the ICP/MS was tuned daily with a tune solution (Inorganic Ventures, Christinaburg, VA, USA) and optimized to meet the manufacturer's recommendations using a daily performance solution. Every day, a certified standard (AccuStandard, Inc., New Haven, CT, USA) was used for the calibration curve and a second source certified standard was used for calibration verifications, internal standards, and spikes (Inorgranic Ventures). The calibration was performed creating a calibration curve from 1 – 200 µg/kg for arsenic, cadmium, copper, and lead, and 5 – 1000 µg/kg for selenium. The internal standards of germanium, indium, and terbium were used for the analysis with the criteria of ≥ 70% of the original calibration blank intensity. For each batch of eighteen samples, a method blank, laboratory control sample, control sample, duplicate, matrix spike, and matrix spike duplicate were prepared along with the samples. The method blank acceptance criteria were less than the method reporting limit for each element analyzed. The laboratory control sample recovery criteria were as follows: arsenic

(55-99%), cadmium (58-90%), copper (53-133%), lead (60-110%), and selenium (39-85%).

B.3.4 Data analysis

Statistical analyses were carried out using R (R Core Team, 2014), using a significance level of α=0.05. Means for each tissue type in each individual were calculated and compared within each tissue type (muscle and liver) across species and region using a two-factor analysis of variance (ANOVA). Significant differences were analyzed using Tukey-Kramer tests for pairwise comparisons. Non-normal or heteroscedastic data that could not be normalized by transformations were analyzed using non-parametric Kruskal-Wallis tests to examine differences between regions or species. Simple comparisons of differences between species or region were performed using t-tests. Averages per tissue type across all individuals of each species (big and longnose skate) were then compared with values reported in the literature for other elasmobranch and teleost species, specifically species from the northeast Pacific Ocean and popular seafood products.

Mercury toxicity can be mitigated by selenium (Kaneko and Ralston 2007) therefore the selenium health benefit value (Se-HBV) was calculated based on the methods of Ralston (2008). Specifically, mercury and selenium concentrations (mg/kg) were converted to molar concentrations (µmol/kg) and the Se-HBV was calculated as:

$$Se - HBV = \left[\left(\mu mol\,\frac{Se}{kg}\right) * (Se\!:Hg)\right] - \left[\left(\mu mol\,\frac{Hg}{kg}\right) * (Hg\!:Se)\right] \qquad \text{(B1)}$$

where Se:Hg is the molar ratio of selenium (Se) to mercury (Hg) and Hg:Se is the molar ratio of mercury to selenium. A positive Se-HBV value indicates an overall health benefit whereas a negative value indicates an overall health risk, with the magnitude being proportional to the benefit or risk.

Finally, to translate the nutritional value and contaminant load of skates from the GOA into a quantitative estimate of the seafood market demand for these skates, the net cardiovascular risk/benefit ratio of consuming skates was calculated using the equation in Ginsberg and Toal (2009). This equation represents a quantitative approach to developing fish consumption advice on individual species, but can also be used to estimate the future consumption of, and therefore demand for, certain products based on the perception of the product by consumers (Lando and Zhang 2011). The Ginsberg and Toal (2009) equation only uses the values of fatty acid and mercury content as these are the most recognizable benefit and risk of consuming seafood. Data from skates were inserted in the following equation:

$$\left[\left(\frac{omega{-}3\ FA\ mg}{meal}\right)*\left(\#\frac{meals}{week}\right)*\left(\frac{1\ week}{7\ days}\right)*\left(\frac{14.6\%\ lower\ risk}{100\ mg\ omega{-}3\ FA}\right)\right]-\left\{\left[\left(\frac{hair\ Hg\ change}{fish\ meal}\right)*\left(\frac{\#\ meals}{week}\right)\right]-(0.51\ ppm\ hair\ Hg)\right\}*\left(\frac{23\%\ higher\ risk}{1\ ppm\ hair\ Hg}\right) \quad \text{(B2)}$$

The net risk/benefit ratio of consuming skate muscle was then compared with the ratio from consuming other common seafood products from the GOA to gauge the level of potential future demand for skate products. Because only raw livers were analyzed here, and not the processed liver oil supplements, we did not think it appropriate to conduct the risk/benefit analysis on the liver tissues.

B.4 Results

B.4.1 Skate samples

Big skate individuals collected and analyzed for this study ranged between 92 and 175 cm total length (TL) with a mean TL of 125.8 cm (95% confidence intervals (CI): 116 – 135), and between 6.02 and 42.67 kg total weight with a mean weight of 16.1 kg (CI: 11.7 – 20.5). Longnose skates ranged between 109 and 133 cm TL with a mean TL of 121.2 cm (CI: 118.1 – 124.2), and between 7.45 and 17.6 kg total weight with a mean of 11.3 kg (CI: 10.2 – 12.3). Based on age and growth equations developed by Gburski et al. (2007), the big skates ranged between 4 and 14 years of age (mean: 8.8, CI: 7.6 – 9.9) and the longnose skates between 15 and 25 years of age (mean: 19.4, CI: 18.3 – 20.5) (Table B-1). Longnose skates were significantly older than big skates ($t=13.2231$, $p<0.0001$) but skates from Cordova and Kodiak (species combined) were not significantly different in age ($t=0.7062$, $p=0.4844$). This size and age range was representative of the skate landings in the GOA (Ormseth and Matta 2011). On average, the wing muscles constituted 34% (3.4% SD) of the mass of big skates and 36% (1.9% SD) of longnose skates, while the liver was 6% (1.6% SD) of the mass of big skates and 8% (2.5% SD) of longnose skates.

B.4.2 Proximate composition analysis

The largest part of the skate wing muscle analyzed for this study was water, with a mean moisture content of 83% (0.9% SD) for big skates and 83% (0.6% SD) for longnose skates. Mean lipid content was 1.2% (0.03% SD) for big skates and 1.2% (0.04% SD) for longnose, while mean protein content was 14.7% (0.8% SD) for big skates and 14.7% (0.7% SD) for longnose skates. Inorganic ash content never exceeded 0.09% for either species (Figure B-3). A two-factor ANOVA indicated no significant differences in ash content among species ($F_{1,36}$=0.1165, p=0.7349) or region ($F_{1,36}$=0.4699) as well as no difference in moisture among species ($F_{1,36}$=0.0359, p=0.8507) or region($F_{1,36}$=2.2680, p=0.1408) in wing muscle, but did show a significant difference in protein content between regions (Species: $F_{1,36}$=0.1115, p=0.740308; Region: $F_{1,36}$=11.8012, p=0.001476). Although the wing muscle of all skates from Kodiak were significantly higher in protein than those from Cordova (Kodiak=15.1%, Cordova=14.4%, p_{adj}=0.0014757) this difference is relatively small and probably not biologically relevant. There was a significant interaction between species and region for lipid content (Species: $F_{1,36}$=0.1925, p=0.6634; Region: $F_{1,36}$=24.5338, p<0.0001; Interaction: $F_{1,36}$=26.9320, p<0.0001), which was mainly driven by longnose skates (Figure B-3B) with significantly less lipid content than the overall average lipid content in Kodiak (0.8%) and more than average lipid content in Cordova (1.6%).

Liver tissue was characterized by high lipid content, between 50 and 65% (Figure B-3B), except for one outlier individual, a longnose skate from Kodiak, which had a clearly shrunken and wilted liver with only 23% lipids. Because this was such a departure from all other individuals, this liver sample was excluded from all subsequent figures and analyses, and the mean lipid content was 52.5% (4.8% SD) for big skates and 57.5% (7% SD) for longnose skates. Mean moisture content in livers was 40.5% (4.3% SD) in big skates and 34.7% (7.9% SD) in longnose skates, and overall varied between 25% and 48%, which is most likely do to an inverse relationship between lipid and moisture content in the liver tissues. Mean protein composition was 5.8% (1.9% SD) for big skates and 7% (2.1% SD) for longnose skates. Ash composition varied between 0.3% and 1.9% (Figure B-3). There were significant differences between species/region groups in all four components of the proximate composition of livers, but in all four cases the interaction term was significant, making further interpretation of the results difficult. This difference was driven primarily by longnose skates from Kodiak which had significantly lower moisture (Species: $F_{1,35}$=25.204, p<0.0001; Region: $F_{1,35}$=44.179, p<0.0001; Interaction: $F_{1,35}$=29.931, p<0.0001) and ash (Species: $F_{1,35}$=23.9765, p<0.0001; Region: $F_{1,35}$=5.0829, p=0.03052; Interaction: $F_{1,35}$=6.4065, p=0.01602) contents and significantly greater protein (Species: $F_{1,35}$=7.0044, p=0.012103; Region: $F_{1,35}$=3.1810, p=0.083171; Interaction: $F_{1,35}$=12.8665, p=0.001012) and lipid (Species: $F_{1,35}$=15.105, p=0.0004329; Region: $F_{1,35}$=31.764, p<0.0001; Interaction: $F_{1,35}$=13.324, p=0.0008473) contents than the other three species/region combinations (Figure B-3).

B.4.2.1 FAMEs

The fatty acid profiles were very similar between big and longnose skates in both muscle (Table B-2) and liver tissues (Table B-3). In muscle, the majority of fatty acids present were polyunsaturated fatty acids, and of these, omega-3 fatty acids were the largest component, specifically DHA. Omega-3 (ω-3) fatty acids were six to twelve times more abundant than omega-6 (ω-6) fatty acids, and polyunsaturated fatty acids (PUFA) were 1.4 to 1.6 more abundant than saturated fatty acids (SAFA). In livers, mono and polyunsaturated fatty acids (MUFA) were equally abundant, and the majority of the polyunsaturated fatty acids were omega-3s, which were six to ten times more abundant than omega-6 fatty acids. As in muscle, DHA was the most common omega-3 fatty acid. In livers, polyunsaturated fatty acids were 1.5 to 2 times more abundant than saturated fatty acids.

B.4.3 Trace elements and heavy metals

B.4.3.1 Mercury

Total mercury content in skate muscle tissue varied between 0.02 and 0.61 mg/kg wet weight, and varied between 0.01 and 0.36 mg/kg wet weight in liver tissue (Figures B-4 and B-5). Overall, muscle samples (mean = 0.21 ± 0.18 SD) were higher in total mercury than liver samples (0.07 ± 0.07SD) (K-W: $\chi^2_1 = 22.1903$, $p < 0.0001$). In muscle, mercury content was significantly higher in samples from Cordova (mean = 0.28 mg/kg ± 0.19 SD) than in samples from Kodiak (mean = 0.14 ± 0.14 SD) (K-W: $\chi^2_1 = 5.8095$, $p = 0.01594$), as well as significantly higher in longnose skates (mean = 0.34 ± 0.18 SD) than in big skates (mean = 0.09 ± 0.06 SD) (K-W: $\chi^2_1 = 25.1016$, $p<0.0001$). Although there was no significant correlation between weight and mercury content across all individuals ($F_{1,38} = 0.8012$, $p = 0.3764$, $r^2 = 0.02065$), there was a significantly positive relationship between age and mercury content ($F_{1,38} = 67{,}05$, $p<0.0001$, $r^2 = 0.6287$) (Figure B-5). In liver tissue, mercury content was again significantly higher in samples from Cordova (mean = 0.1 mg/kg ± 0.08 SD) than in samples from Kodiak (mean = 0.03 ± 0.04 SD) (K-W: $\chi^2_1 = 21.7913$, $p<0.0001$), but there was no significant difference between longnose skates (mean = 0.09 ± 0.09 SD) and big skates (mean = 0.04 ± 0.03 SD) (K-W: $\chi^2_1 = 3.4866$, $p = 0.06187$).

Several guidelines on the methylmercury content of fish have been established to help consumers determine how much of which fish species they want to eat. The US EPA recreational fishing screening value for methylmercury content is 0.4 mg/kg (US EPA 2009), while the FDA has set action levels for methylmercury at 1.0 mg/kg, above which they will take legal action to remove the product from the market (FDA 2014). For current Alaskan skate products (big and longnose skate wing muscle), mean mercury content for both big and longnose skates were below the FDA action value and US EPA screening value (Figure B-5). In addition, no individual sample had a value above 1.0 mg/kg, but six longnose skates did exceed the 0.4 mg/kg US EPA guideline level.

Longnose skates in this study had muscle mercury levels equivalent to the average levels found in Pacific halibut ($t = 1.163$, $p = 0.245$), while big skates had lower mercury levels equivalent to Chinook salmon (*Oncorhynchus tshawytscha*) ($t = 1.740$, $p = 0.083$). Overall, skates had much lower mercury levels than other elasmobranchs, such as salmon sharks (*Lamna ditropis*) ($t = 28.809$, $p < 0.0001$) and Pacific spiny dogfish (*Squalus suckleyi*) ($t = 12.862$, $p < 0.0001$), as well as lower levels than other fish species such as yelloweye rockfish (*Sebastes ruberrimus*) ($t = 7.815$, $p < 0.0001$) and northern pike (*Esox lucius*) ($t = 6.423$, $p < 0.0001$). However, skates had similar mercury levels as sablefish (*Anoplopoma fimbria*) ($t = 1.011$, $p = 0.313$) (Figure B-5).

B.4.3.2 Arsenic, cadmium, selenium, copper and lead

Of the other heavy metals (Figure B-6), total arsenic was elevated in skate muscle tissues (14.0 mg/kg ± 7.9) and less so in liver tissue (5.43 mg/kg ± 2.3). Cadmium was only detected in liver samples at an average level of 0.25 mg/kg (0.22 SD), much higher than in the muscle of other species in the North Pacific (Figure B-7B). This is not surprising because heavy metals such as cadmium usually accumulate in organ tissues (ATSDR 2012). At this concentration of cadmium, the US EPA recommends eating less than eight servings of 0.227 kg per month of skate liver (US EPA 2009). Similarly, selenium was higher in skate liver tissue (0.854 mg/kg ± 0.38) than in skate muscle (0.33 mg/kg ± 0.08), but both of these levels are well within the range of the US EPA guidelines for unrestricted consumption (US EPA 2009). Copper levels were also higher in skate liver than muscle (8.36 mg/kg ± 9.11 in liver and 0.18 ± 0.09 in muscle), although both were below the FAO guideline of 30 mg/kg (Nauen 1983). Lastly, lead was not detected in any skate sample, muscle or liver, except for one big skate from Kodiak, which had 0.035 mg/kg in its muscle tissue. This level is much lower than the Food and Agriculture Organization (FAO) recommended limit of 0.5 mg/kg (FAO 2001).

All selenium health benefit values (Se-HBV) for the skate samples were positive, meaning that there is a net beneficial interaction between mercury and selenium. Because mercury values in the livers were relatively low and selenium values were high, the Se-HBV were very high in all liver samples, with average values of 1154.5 (765.6 SD) for big skates and 208.8 (97.2 SD) for longnose skates. Big skates had significantly higher Se-HBV values than longnose skates ($F_{1,37} = 32.4766$, $p<0.0001$), and Kodiak samples had higher Se-HBV values than Cordova samples ($F_{1,37} = 4.0924$, $p = 0.05$). Muscle tissues had higher mercury and lower selenium so although all the values were positive, averages were lower, with big skates 109 (109 SD) having significantly higher Se-HBV values than longnose skates 8.8 (5.4 SD) ($F_{1,37} = 5.8674$, $p = 0.02044$). Muscle samples from Kodiak also had higher SE-HBV values (95.4 ± 195SD) than samples from Cordova (22.3 ± 22.2) but this difference was not significant ($F_{1,37}$ = 3.1201, p = 0.08558).

B.4.4 Risk/benefit analysis of skate consumption

When all individuals of both species are considered together, there is no net significant cardiovascular benefit or risk of consuming skate muscle (3.62% cardiovascular improvement ± 27.54%), but the high standard deviation shows that there is a lot of variation in the risk/benefit ratio (Table B-4). Big skates from Kodiak had the most beneficial and consistent risk/benefit ratio (27.55% ± 7.99%), followed by big skates from Cordova (14.09% ± 9.93%). Longnose skates were much more variable, with individuals from Kodiak having a small non-significant net benefit (3.15% ± 27.00%) and individuals from Cordova having a non-significant net risk (-30.33% ± 18.84%). In fact, every individual longnose skate from Cordova had a net cardiovascular risk. Differences between species and regions were significant (Interaction: $F_{1,36}$ = 3.2173, p = 0.08; Species: $F_{1,36}$ = 35.859, p<0.0001; Region: $F_{1,36}$ = 16.679, p = 0.0002275), with significantly higher risk for longnose skates (Tukey HSD: p = 0.00000007) and skates from Cordova (Tukey HSD: p = 0.0002275).

On average, consuming skates from the GOA had a risk/benefit ratio comparable to consuming Pacific halibut (Table B-4). However, consuming only big skates, especially from Kodiak, provides a much higher net cardiovascular benefit at levels between pollock (11.07%) and Chinook salmon (40.80%) and sablefish (49.49%) (Loring et al. 2010). Pacific herring (*Clupea pallasii*) had the highest benefit with a 71% cardiovascular improvement (Ginsberg and Toal 2009). In contrast, consuming longnose skates from

Cordova carries a net risk (-30.30%), which lies between eating yellowfin tuna *Thunnus albacares* (-7.0%) and swordfish (-49.0%). However, skates were substantially less risky to consume than sharks (-55%), which is important to note since sharks and skates are closely related and without skate-specific information, it may be attractive to use shark data as a surrogate for skates.

B.5 Discussion

The muscle in the pectoral fins or "wings" of big and longnose skates from the GOA provides a lean source of protein with a fatty acid profile rich in healthy omega-3 fatty acids that have neurological and cardiovascular benefits (Racine and Deckelbaum 2007). The proximate composition of the skate muscle is similar to that of other white muscle fish such as Pacific cod and Pacific halibut (NOAA 1987). In particular, skate muscle is very similar to Pacific halibut in lipid (1.6%) and omega-3 PUFA content (NOAA 1987). In contrast, average Chinook salmon lipid composition has a lower percentage of omega-3 fatty acids, but salmon muscle has such a higher content of lipids (13.2%) than skate muscle, resulting in total omega-3 fatty acids content per serving being much greater in salmon (USDA 2011). The high relative PUFA content in skate muscle is most likely due to these muscle tissues being low in overall lipids. Low lipid tissues are known to be relatively high in phospholipids, which contain a larger proportion of PUFA than other lipid classes (Ackman et al. 1980). Skate livers had higher lipid content than Pacific halibut, Pacific cod or pink salmon (*Oncorhynchus gorbuscha*) livers (Bechtel and Oliveira 2006) but had a similar fatty acid profile, making skate livers much richer in omega-3 fatty acids than livers of these other species. The thornback ray (*Raja clavata*), a closely related and economically important skate species in the North Atlantic, had similar but slightly higher muscle lipid (3.39%) and protein (18.58%) content, and lower water (76.51%) content than big and longnose skates (Colakoglu et al. 2011).

On the other hand, arsenic, mercury, copper and selenium were found in skate muscle tissues. Total arsenic levels were higher in skate wing muscles than the recommended US EPA limits (US EPA 1997). However, most of this arsenic is likely organic arsenic (Chew 1996) such as in the North Sea where toxic inorganic arsenic constituted less than 1% and 3 % of the total arsenic in the lesser spotted dogfish (*Scyliorhinus canicula*) and thornback ray, respectively (De Gieter et al. 2002). Although this suggests low arsenic toxicity of big and longnose skates, it would be prudent to further study the amount of inorganic arsenic in big and longnose skates. Copper was found in relatively high concentration in skate livers, most likely because similar to cadmium, copper tends to accumulate in internal organs (Grosell et al. 2003). Although these levels in skates are still below consumption guidelines, they were higher than the 0.8 mg/kg levels found in Pacific sleeper sharks (*Somniosus pacificus*) (McMeans et al. 2007) and the 4.07 mg/kg found sandbar sharks (*Carcharhinus plumbeus*) (Endo et al. 2008). This may reflect a higher concentration of environmental copper in the GOA (Grosell et al. 2003).

Skates from the GOA are relatively low in mercury compared to other elasmobranchs or long-lived fishes (Gerlach and Teas 2012; Figure B-5). Current fish consumption advisories from the FDA and the World Health Organization set safety limits of methylmercury content in fish at 1 μg/g wet weight (or 1 mg/kg). Several studies have examined the level of mercury in elasmobranchs (sharks, rays and skates) and show that the range of mercury levels in muscle tissues often exceed this safety limit, including in sharks near Florida (0.11

to 2.3 mg/kg; Adams and McMichael 1998), Hawaii (0.98 to 1.81 mg/kg; Kaneko and Ralston, 2007), Northwest Mexico (0.05 to 3.36 mg/kg; Hurtado-Banda et al., 2012) and shark meat from Korean markets (2.11 mg/kg; Kim et al. 2012). In addition, mercury levels in some skates seem to be just as high in the Mediterranean, with starry rays (*Raja asterias*) having total mercury levels of 0.09 to 1.78 mg/kg (Storelli et al. 2003). The results in Storelli et al. (2003) also indicate that 68 to 100% of the total mercury in muscle tissues of these skates is methylmercury. Compared to those studies above, skates in the GOA have substantially less mercury in their tissues, with similar levels as the thornback ray from the North Atlantic, which was found to have a range of muscle mercury content of 0.007 to 0.270 mg/kg (Dixon and Jones 1994). Fish consumption advice from the State of Alaska lists big skates as unrestricted, while the recommended limit for longnose skate consumption is 12 meals per month (Hamade 2014).

The proximal cause of mercury toxicity is usually the sequestration of selenium compounds (notably selenoenzymes) by methylmercury. Therefore, ingesting sufficient amounts of selenium with mercury could offset the risks associated with mercury toxicity (Ralston and Raymond, 2010) and the true risk of seafood consumption should be calculated using Se-HBV (Ralston 2008). The positive Se-HBV calculated here for skates indicate that there is sufficient selenium in skate tissues to counteract the toxic effects of mercury ingested. In comparison, mako sharks (*Isurus oxyrinchus*) have a negative Se-HBV indicating that the mercury risk associated with consuming this species is substantial (Kaneko and Ralston 2007). The positive Se-HBV for skates in the GOA provides further evidence that consuming skate muscle tissue is nutritionally beneficial and that it is appropriate to consider it as a viable product for the global fish market.

Skates from the GOA also show promise as an economically viable source of fish liver oil, with very high lipid content in their livers and a high proportion of polyunsaturated fatty acids. Based on the average big and longnose skate catches from 2011 to 2013, 203 metric tons of liver biomass could have been retained in that time frame, increasing the revenue from skates. Fisheries managers in Alaska are unlikely to drastically increase the allowable catch of skates due to their life history characteristics (Dulvy and Reynolds 2002). However, increasing the value obtained from each skate harvested would increase the revenue of the fishery without removing additional skate biomass. Elasmobranchs tend to store less mercury in their livers than in their muscles (Hurtado-Banda et al. 2012), which is consistent with the results presented here. Studies on fish oil supplements show that even those supplements derived from shark livers have negligible amounts of mercury, which is due to both the lower mercury content in the liver, but also the processing of the liver oils which removes some of the heavy metals (Foran et al. 2003). The only other study that has looked at the nutritional content of skate in the GOA examined the livers of five longnose skates from Kodiak Alaska and also found high levels of both EPA and DHA (16 and 17.7%, respectively) and high amino acids (Wu et al. 2011). Although mercury may not be a concern for skate liver oil production, cadmium levels in livers were very high for both species. Cadmium has been found to be a toxic to all life, even at low concentration (Borgmann et al. 2005), causing birth defects and genetic mutations (Nordberg et al. 2007). Cadmium naturally occurs in low concentrations in the environment, around 1 ppb (Nordberg et al. 2007), but through bioaccumulation and biomagnification can reach high levels in fish, especially in organs. It will therefore be important to determine whether cadmium can be removed by a low-cost method during processing of the liver oils.

The variability in the risk/benefit ratio of skate muscles in the GOA is mostly due to the variability in the mercury content, which can be explained by differences in regions, species and size/age. Mercury content was higher in skates from Cordova than skates from Kodiak. Cordova skates were caught in waters within Prince William Sound, a more closed system heavily influenced by glacial and alluvial runoff that could carry land-based mercury into the coastal waters. In contrast, Kodiak skates were caught on the continental shelf of the GOA, where the Alaska coastal current provides constant water flow. Although skates are capable of long-range horizontal movements, tagging studies suggest that most do not move across large geographic areas (King and McFarlane 2010; Farrugia et al. 2016), and differential environmental mercury levels could explain the regional differences in skate mercury content. Unsurprisingly, mercury content was found to be higher in the longer-lived species (longnose skate), which bioaccumulated more mercury over a longer period of time in its tissues. However, since the growth curves for big and longnose skates are different, consumption advisories for GOA skates cannot be based on size alone. The only skates that were found to be above the 0.4 mg/kg mercury limit in this study were longnose skates over 18 years old, corresponding to a size of over 118 TL (Gburski et al. 2007). Based on the fishery length composition of longnose skate catches, up to 34% of the landed longnose skates could be old enough to have accumulated mercury to over the 0.4 mg/kg level (Ormseth and Matta 2011). No big skates in this study were found to have mercury levels above 0.4 mg/kg.

This large variability in mercury between species and regions shows the complexities involved in extrapolating nutritional value and contaminant content data across taxa and regions. There are far more studies available on sharks than skates, so it can be attractive to simply use the available data from other species or from the same species in other regions. However, this can lead to erroneous conclusions, indicating a need to conduct this type of research on the actual fish being harvested, sold and consumed (Sunderland 2007). Not doing so could have negative economic consequences if local fish are deemed unsafe when they actually are safe to be consumed, or, on the contrary, expose humans to negative health consequences if contaminated fish are presumed to be safe.

This study provides an initial look into the nutritional value and contaminant load of skates from two regions in the GOA. Because the purpose of this study was to establish baseline values in skate tissues, the sample size (40 individuals) was low, and a larger scale study should be conducted. Perhaps the most important variable that was omitted in this study was seasonality. Including skates from different seasons could be particularly informative for the nutritional content of the skate, as the condition of fish likely varies on an intra-annual basis, leading to different levels of lipids in the tissues among seasons (Kizevetter, 1971). For example, in this study, longnose skates off Kodiak had significantly higher lipid content and lower water content in their liver than big skates and longnose skates from Cordova, indicating that the Kodiak fish may have been in better condition. Further, the risk/benefit ratio calculated here and in the literature (Ginsberg and Toal 2009; Loring et al. 2010) includes the highest profile components of nutritional value (omega-3 fatty acids) and contaminants (mercury), which are also most likely to drive changes in demand for the product. But other factors could be included to provide a more holistic assessment of the risks and benefits, such as vitamins, amino acids, minerals and organic contaminants (e.g., polychlorinated biphenyls). Finally, other skate co-products, such as cartilage, could be developed for commercial markets. For instance, shark cartilage is being used in dietary supplements and calcium pills (Leblond et al. 2008; Kim 2004) and skate cartilage could address this demand.

B.6 Conclusions

Muscle from big and longnose skates caught in the GOA provide a source of lean protein with a healthy fatty acid profile, and their livers are a very good source of omega-3 rich fish oil. These skates are currently in demand on the global market, and there is no indication that the nutritional value or contaminant load of the skates tested would lead to a decrease in future demand. Although some species of skates may have a greater health benefit than others, there is an overall benefit to consuming skate muscle. Even the individuals that presented a higher consumption risk had a better risk/benefit ratio, and lower contaminants than high-priced alternatives such as sharks and swordfish, which are still in demand despite advisories against excessive consumption. In fact, the nutritional value and trace element content found in this study are very similar to those of the thornback ray, an economically important fishery skate species in the North Atlantic.

Because the actual liver product (skate liver oil supplements) was not tested in this study, it was not appropriate to determine the risk/benefit ratio of skate livers here; this should be done before skates are used as a source of liver oil supplements. Even though our contaminant level results are of concern and need to be addressed before oil production could begin, additional value from producing liver oil from the captured skates would increase the revenue of this fishery without increasing harvest, and would therefore help increase the profitability of a potential fishery. In the past decade, fishers have received an exvessel price of up to US$1/kg for skates leading to annual revenue of over US$2 million from the sale of this bycatch species. As such, a sustainable and profitable skate harvest in the GOA may increase the resilience of local fishing communities.

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Table B-1. Mean morphological characteristics of skates used in the nutrition and contaminant analyses (mean±SD).

Species	Big Skate			Longnose Skate			Overall
Region	Cordova	Kodiak	All	Cordova	Kodiak	All	
Total length (cm)	127.4±14.1	124.3±27.4	125.8±21.3	123.4±5.6	118.9±7.9	121.2±7.0	123.5±15.8
Disc width (cm)	95.8±11.9	95.5±21.5	95.7±16.9	87.4±5.7	84.7±7.6	86.1±6.7	90.9±13.6
Whole weight (kg)	16.01±6.9	16.19±12.8	16.10±10.0	11.73±2.4	10.83±2.4	11.28±2.4	13.69±7.6
Wing weight (kg)	5.73±2.6	5.05±3.7	5.39±3.2	4.32±0.9	3.82±0.9	4.07±0.9	4.73±2.4
% Wing[a]	35.7±3.5	31.9±2.1	33.8±3.4	36.8±1.4	35.2±2.1	36.0±1.9	34.9±3.0
Liver weight (kg)	0.95±0.7	1.36±1.5	1.16±1.2	0.71±0.3	1.05±0.4	0.88±0.4	1.02±0.9
% Liver[a]	5.5±1.5	7.0±2.2	6.3±2.0	6.0±1.5	9.6±1.9	7.8±1.9	7.0±2.3
Sex ratio (male:female)	1:1	1:9	3:7	1:1	1:1	1:1	2:3
Age from VB[b] (years)	9.4±2.0	8.1±3.2	8.8±2.7	20.0±2.2	18.7±2.7	19.4±2.7	14.1±5.9

[a] % Wing and % Liver = percent of the body weight that is wing muscle and liver, respectively.

[b] VB = age determined using the von Bertalanffy growth curve with parameter values from Gburski et al. (2007).

Table B-2. Fatty acid (FA) profile (% total fatty acids) of skate muscle tissue (mean±SD), including the five most abundant fatty acids.

Fatty Acid	Big Skate			Longnose Skate			Overall
	Cordova	Kodiak	All	Cordova	Kodiak	All	
SAFA	29.9±3.8	31.7±2.8	30.8±3.4	33.0±1.3	33.1±2.0	33.0±1.7	31.9±2.9
MUFA	24.0±5.4	21.2±2.4	22.6±4.3	18.2±1.7	20.8±3.2	19.5±2.8	21.0±3.9
PUFA	45.9±4.8	46.0±4.0	46.0±4.3	48.5±1.7	45.0±3.1	46.8±3.0	46.4±3.7
∑ ω-3	37.4±3.7	41.9±3.8	39.7±4.3	42.1±1.8	40.2±3.2	41.2±2.7	40.4±3.6
∑ ω-6	6.8±2.3	3.6±1.0	5.2±2.4	5.8±1.0	3.9±0.9	4.8±1.3	5.0±1.9
∑ ω-3/∑ ω-6	6.0±1.9	12.4±3.1	9.2±4.1	7.6±1.5	10.8±2.3	9.2±2.5	9.2±3.4
PUFA/SAFA	1.6±0.3	1.5±0.2	1.5±0.2	1.5±0.1	1.4±0.1	1.4±0.1	1.5±0.2
20:5ω3 (EPA)	6.7±1.7	9.3±1.3	8.0±1.3	4.8±1.2	7.1±0.9	6.0±1.6	7.0±2.1
22:6ω3 (DHA)	24.7±2.7	26.4±2.6	25.6±2.6	30.8±1.3	26.2±3.4	28.5±3.4	27.0±3.4
16:0	22.2±3.4	23.3±2.3	22.7±2.9	25.1±1.5	23.5±2.2	24.3±2.0	23.5±2.6
18:1ω9 cis	8.5±1.0	7.3±0.7	7.9±1.0	8.3±0.9	7.4±1.5	7.9±1.3	7.9±1.1
22:5ω3	5.0±0.9	4.9±0.9	4.9±0.9	5.9±0.7	5.5±0.8	5.7±0.7	5.3±0.9

SAFA = saturated fatty acid, MUFA = monounsaturated fatty acid, PUFA = polyunsaturated fatty acid, EPA = eicosapentaenoic acid, DHA = docosahexaenoic acid, ω-3 = omega 3 FA, ω-6 = omega-6 FA

Table B-3. Fatty acid (FA) profile (% total fatty acids) of skate liver tissue (mean±SD), including the five most abundant fatty acids.

	Big Skate			Longnose Skate			Overall
Fatty Acid	Cordova	Kodiak	All	Cordova	Kodiak	All	
SAFA	21.7±3.1	20.7±1.2	21.2±2.4	23.0±2.8	22.4±1.6	22.7±2.2	22.0±2.4
MUFA	38.4±2.8	36.0±4.2	37.2±3.7	41.2±4.6	42.5±3.0	41.8±3.8	39.5±4.4
PUFA	37.2±2.2	41.4±3.5	39.3±3.6	33.8±4.1	33.4±2.9	33.6±3.4	36.4±4.5
$\sum$ ω-3	30.3±1.7	35.8±3.6	33.1±4.0	27.1±3.3	27.4±2.8	27.2±2.9	30.2±4.5
$\sum$ ω-6	4.2±0.8	3.5±0.5	3.9±0.7	4.4±0.7	4.1±0.5	4.3±0.6	4.1±0.7
$\sum$ ω-3/$\sum$ ω-6	7.5±1.8	10.4±2.2	8.9±2.5	6.3±1.1	6.7±1.0	6.5±1.1	7.7±2.2
PUFA/SAFA	1.7±0.3	2.0±0.1	1.9±0.3	1.5±0.4	1.5±0.2	1.5±0.3	1.7±0.3
20:5ω3 (EPA)	9.4±2.6	12.3±2.3	10.8±2.8	7.0±2.3	11.3±2.6	9.2±3.3	10.0±3.1
22:6ω3 (DHA)	18.5±3.1	20.1±3.0	19.3±3.1	18.1±2.4	13.4±1.8	15.7±3.2	17.5±3.6
18:1ω9 cis	14.8±3.3	11.9±2.5	13.4±3.3	16.5±2.0	16.3±1.8	16.4±1.8	14.9±3.0
16:0	11.8±2.4	12.4±1.4	12.1±1.9	14.3±2.6	14.1±0.7	14.2±1.8	13.1±2.1
16:1ω7	7.1±1.5	6.8±0.9	7.0±1.2	6.4±1.4	7.1±0.7	6.8±1.1	6.9±1.1

SAFA = saturated fatty acid, MUFA = monounsaturated fatty acid, PUFA = polyunsaturated fatty acid, EPA = eicosapentaenoic acid, DHA = docosahexaenoic acid, ω-3 = omega 3 FA, ω-6 = omega-6 FA

Table B-4. Cardiovascular risk/benefit ratio for big and longnose skates collected near Cordova and Kodiak, Alaska. Other species are shown for comparison. Percentages refer to the percent increase (or decrease) in cardiovascular health based on the balance of risks from mercury toxicity and benefits from omega-3 fatty acids.

Species	Region	Risk/Benefit (%)	Source
Big Skate	Cordova	14.09 ± 9.93	This study
Big Skate	Kodiak	27.55 ± 7.99	This study
Longnose	Cordova	-30.33 ± 18.84	This study
Longnose	Kodiak	3.15 ± 27.00	This study
Skates	GOA[a]	3.62 ± 27.54	This study
Pacific Halibut	GOA	4.21	Loring et al. 2010
Sablefish	GOA	49.49	Loring et al. 2010
Pollock	GOA	11.07	Loring et al. 2010
Chinook Salmon	GOA	40.80	Loring et al. 2010
Shark	Atlantic	-55.00	Ginsberg and Toal 2009
Swordfish	Atlantic	-49.00	Ginsberg and Toal 2009
Yellowfin Tuna	Atlantic	-7.00	Ginsberg and Toal 2009
Herring	Atlantic	71.00	Ginsberg and Toal 2009

[a] GOA = Gulf of Alaska

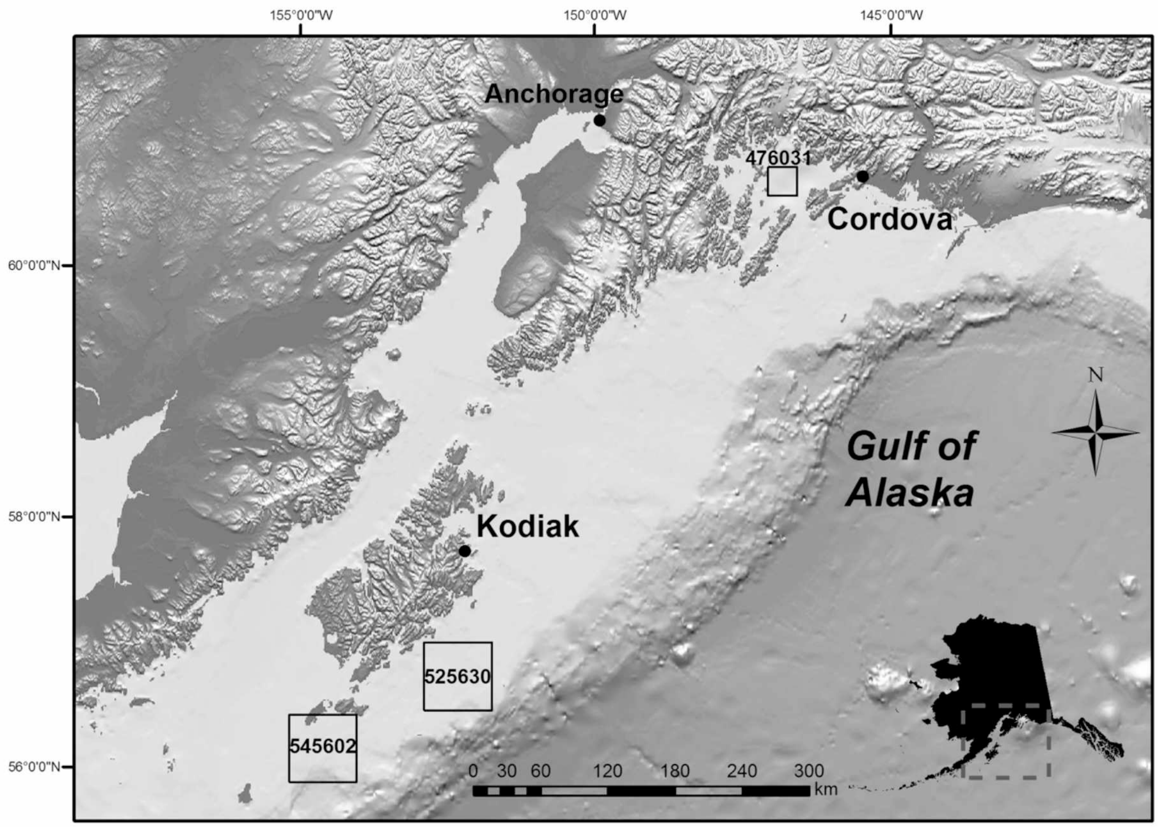

Figure B-1. Map of the Gulf of Alaska (GOA) and the statistical areas from which skates were collected. National Marine Fisheries Service statistical areas are shown in black squares with statistical area numbers, and the nearest landing ports, Kodiak and Cordova are labeled. Inset map shows the location of the sampling area with respect to Alaska.

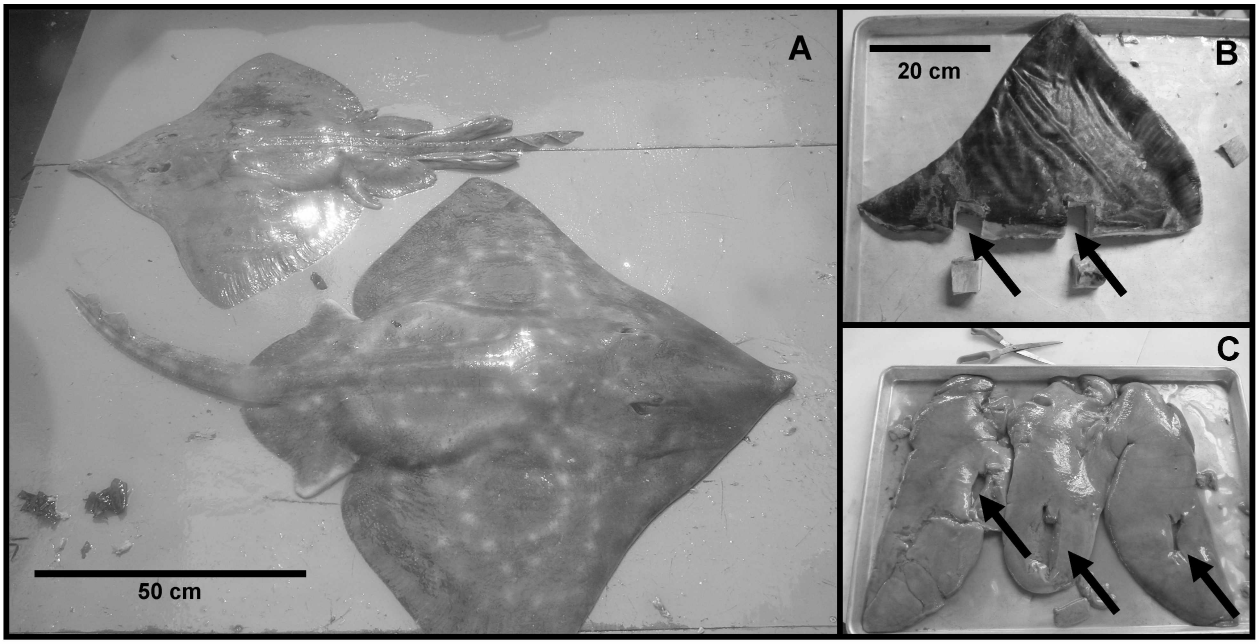

Figure B-2. Pictures of a skates showing the locations where muscle and liver samples were taken. The pictures show a longnose skate (A, top) and a big skate (A, bottom), a big skate wing (B) and a big skate liver (C) showing the locations of tissue samplings (arrows).

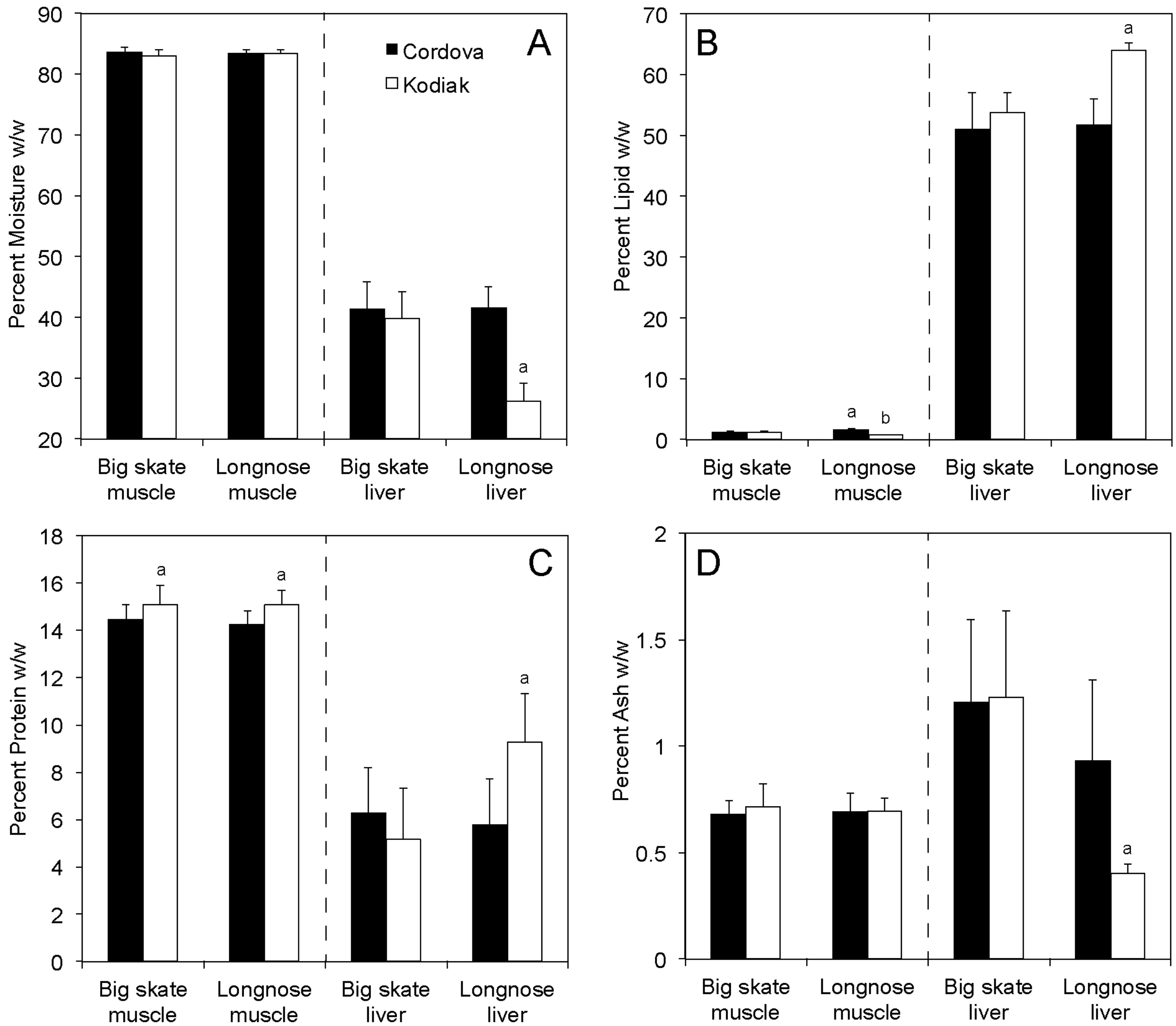

Figure B-3. Proximate composition of skate muscle and liver tissue samples. Data are in percent wet weight (w/w) for big and longnose skates collected near Cordova and Kodiak, including moisture (A), lipid (B), protein (C) and inorganic ash (D). The dashed vertical line separates the muscle and liver samples in each pane. Error bars are 1 SD. Significant differences within a tissue type are designated with a letter.

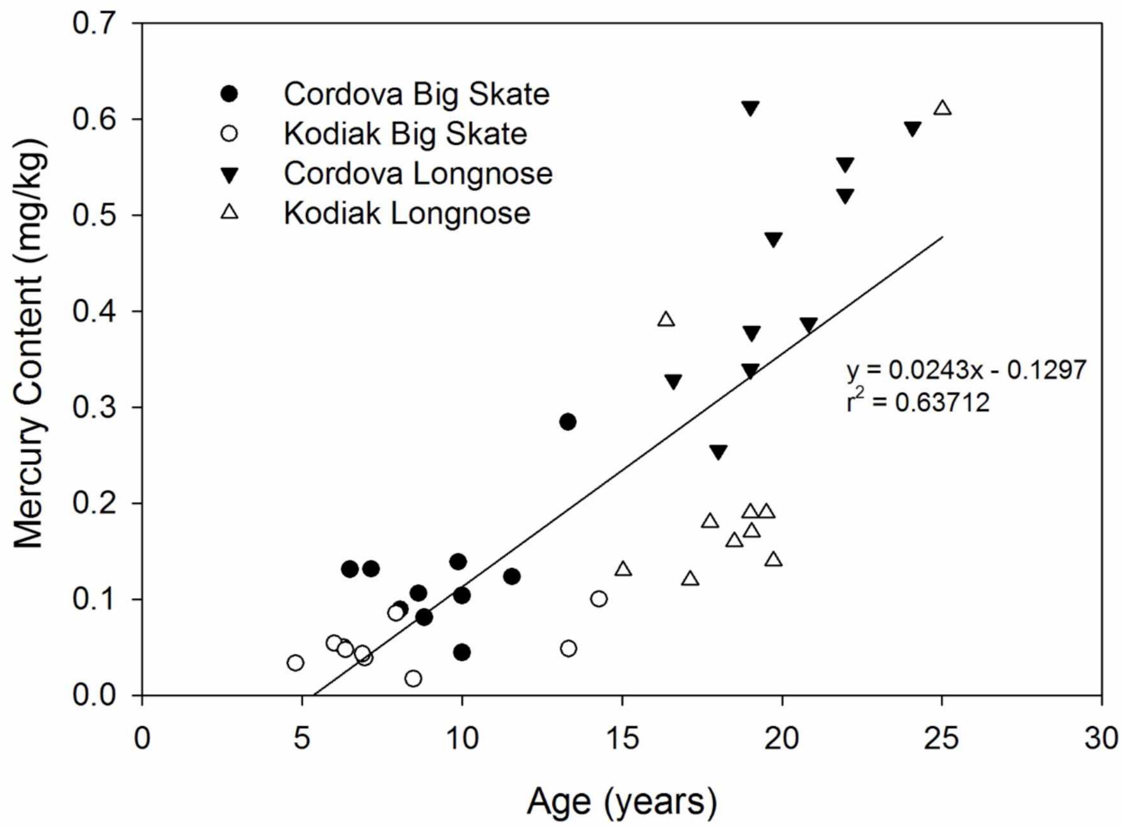

Figure B-4. Mercury content across the age of skates sampled in the Gulf of Alaska. The relationship between age and mercury for big (circles) and longnose (triangle) skates collected near Cordova (closed symbols) and Kodiak (open symbols) is representd by the solid line.

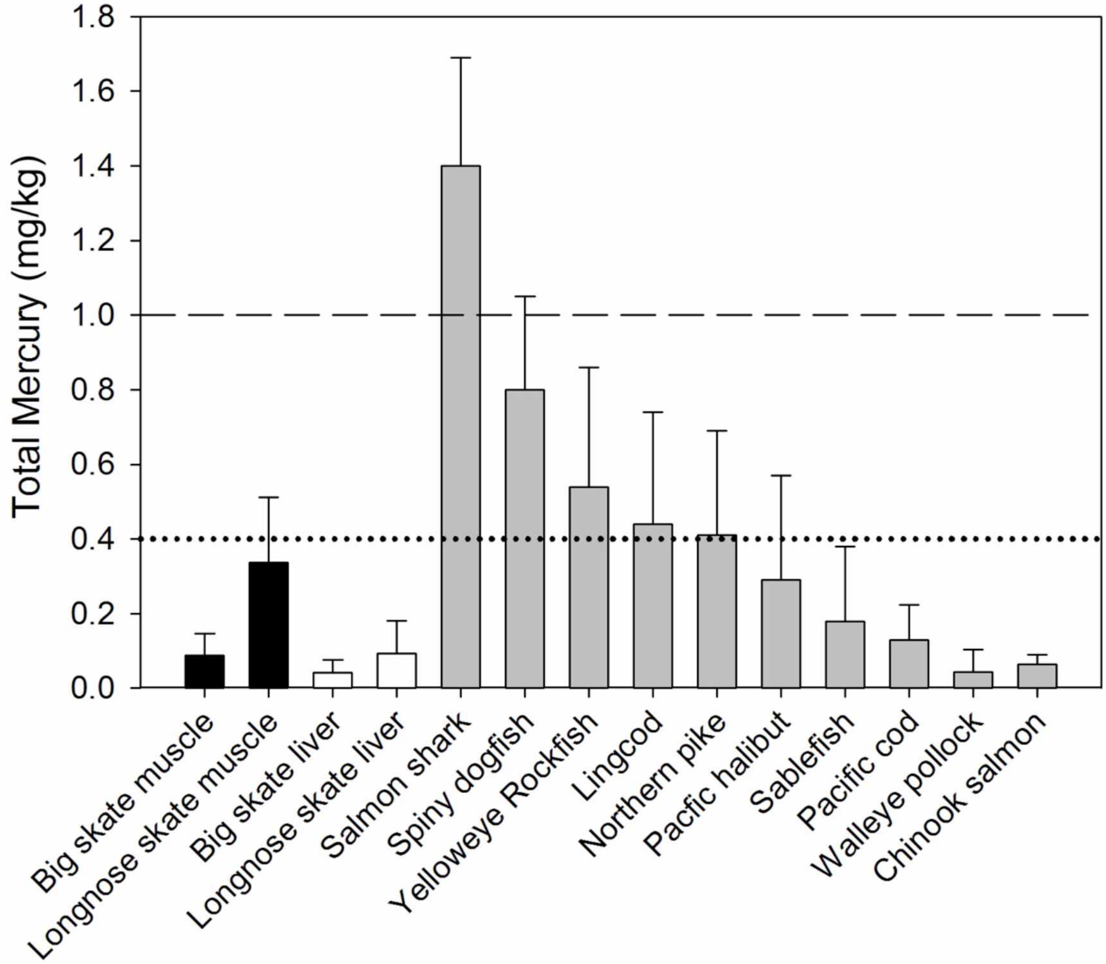

Figure B-5. Average mercury content for skates and other species in the Gulf of Alaska. Mercury content (mg/kg wet weight) is shown for big and longnose skate muscle (black) and liver (white) tissues. Mercury content from other important commercial and subsistence fish species from the North Pacific are shown in grey for comparison (from Gerlach and Teas, 2012). The dotted horizontal line is the Environmental Protection Agency recreational screening value (US EPA, 2009) and the dashed line is the Food and Drug Administration action level (FDA, 2014). Error bars are 1 SD.

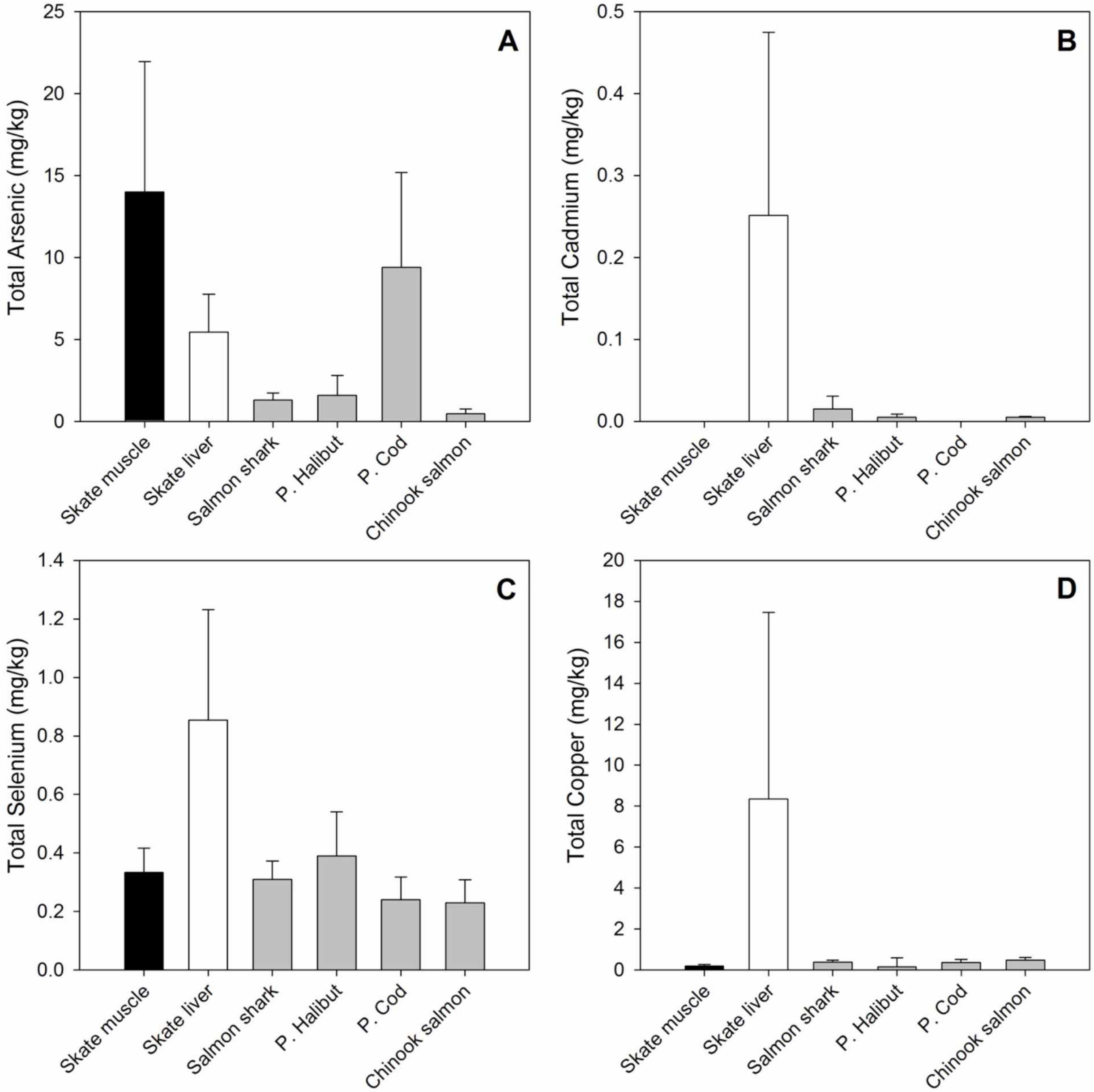

Figure B-6. Heavy metal content of skates and other species from the Gulf of Alaska. Content of arsenic (A), cadmium (B), selenium (C) and copper (D) are shown for muscle (black) and liver (white) samples. Values of muscle tissues for other fish species are shown in grey (data from Gerlach and Teas, 2012) for comparison. Error bars are 1 SD.

Appendix C

Approval letter for project 217575 from the University of Alaska Fairbanks Institutional Animal Care and Use Committee (IACUC)

UNIVERSITY OF ALASKA FAIRBANKS

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909 N Koyukuk Dr. Suite 212, P.O. Box 757270, Fairbanks, Alaska 99775-7270

March 24, 2011

To:	Andrew Seitz, PhD Principal Investigator
From:	University of Alaska Fairbanks IACUC
Re:	[217575-2] Movement patterns and spatially explicit stock assessment of skates in Prince William Sound, Alaska

The IACUC reviewed and approved the New Project referenced below by Designated Member Review.

Received:	March 8, 2011
Approval Date:	March 24, 2011
Initial Approval Date:	March 24, 2011
Expiration Date:	March 24, 2012

This action is included on the March 25, 2011 IACUC Agenda.

The PI is responsible for acquiring and maintaining all necessary permits and permissions prior to beginning work on this protocol. Failure to obtain or maintain valid permits is considered a violation of an IACUC protocol, and could result in revocation of IACUC approval.